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WORLD METEOROLOGICAL ORGANIZATION

COMPENDIUM OF LECTURE NOTES
ON
METEOROLOGICAL INSTRUMENTS
FOR
TRAINING CLASS III AND CLASS IV METEOROLOGICAL PERSONNEL

Prepared by
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VOLUME I

PART 1 — Meteorological instruments

PART 2 — Meteorological instrument maintenance workshops, calibration laboratories and routines

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C O N T E N T S

PART 1 - METEOROLOGICAL INSTRUMENTS

PART 2 - METEOROLOGICAL INSTRUMENT MAINTENANCE WORKSHOPS, CALIBRATION LABORATORIES AND ROUTINES

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P A R T 1

METEOROLOGICAL INSTRUMENTS

FOREWORD

The need for compendia of lecture notes on meteorological instruments for the training of all categories of meteorological personnel has been recognized on many occasions by the Commission for Instruments and Methods of Observation and this view has been endorsed by the WMO Executive Council Panel of Experts on Education and Training. The present publication is intended for use in training Class III and Class IV meteorological personnel. It is based on the corresponding curricula published in the WMO "Guidelines for the Education and Training of Personnel in Meteorology and Operational Hydrology" (WMO-No. 258, third edition, 1985).

This compendium consists of two volumes: Volume I includes Part 1 - Meteorological Instruments, and Part 2 - Meteorological Instrument Maintenance Workshops, Calibration Laboratories and Routines; Volume II includes Part 3 - Basic Electronics for the Meteorologist.

The manuscript for this publication was prepared by Dr. D. A. Simidchiev of the Hydrometeorological Service, Bulgaria, to whom I wish to convey my sincere appreciation and gratitude for this excellent work.

It is confidently hoped that this publication will be useful to students and instructors alike and contribute to the attainment and maintenance of a high standard of technical and scientific training of meteorological personnel throughout the world.

(G.O.P. Obasi)
Secretary-General

INTRODUCTION

An appreciable number of human activities are affected by the weather. In order to minimize the unfavourable effects of atmospheric phenomena on such activities, man has since early times studied the laws governing the weather.

Obtaining knowledge about the weather is an objective of the branch of science generally known as meteorology. Meteorological phenomena are studied through observations, experiments and analytical scientific methods.

The meteorological observation is an evaluation or measurement of one or more meteorological elements. Meteorological observations are either sensory, i.e. taken by a human observer without the use of measuring instruments; or instrumental, which are generally known as meteorological measurements and made by the use of meteorological instruments.

A place at which the evaluation of one or more meteorological elements is carried out regularly is called a meteorological observing station. Meteorological observing stations are classified under the following categories depending on the observation objectives of the station:

(a) Synoptic stations (surface and upper-air);

(b) Climatological stations;

(c) Agrometeorological stations;

(d) Aviation stations;

(e) Special meteorological observing stations.

Meteorological observing stations are established on land or at sea and, ideally, are spaced so as to guarantee adequate meteorological coverage, thus forming a meteorological observing station network. As an example, principal surface synoptic stations should be spaced at intervals not exceeding 150 km and upper-air stations at intervals not exceeding 300 km. A closer spacing of network stations enhances the observation network data output. An optimum spacing of observing stations is one for which cost has been taken into account, depending on the purpose for which the data are to be used, the spatial and temporal variability of the meteorological element observed and the nature of the topography of the Earth's surface over which the network is to be established. A strict conformity exists as regards observing programmes, siting and exposure of meteorological instruments at meteorological network stations.

Depending on the kind of observations made, the meteorological observing stations of a network are usually connected to a collecting centre by a suitable telecommunication link. The data collected are subjected to quality control before being disseminated to users.

Network observing stations are subject to regular inspection in order to ensure the high standard of observational data. For the same purpose, a station's facilities and instruments are maintained by the Meteorological Service on a regular basis.

CHAPTER 1

MEASUREMENT OF METEOROLOGICAL VARIABLES

1.1 Specific features of meteorological measurements

Physics is concerned with the measurement of physical variables. In order to discover the value of a quantity with a predetermined accuracy, a number of conditions must be fulfilled. These conditions concern the exposure of the instrument to the measured variable, the instrument's calibration, scale graduation, transient behaviour, etc. and, last but not least, the operator's professional skill.

With the measurement of meteorological variables, most of which are essentially physical variables, the problems are even more complicated because of the specific features of meteorological phenomena.

Atmospheric processes are taking place on time and space scales completely different from those of laboratory-observed phenomena. For the investigation of phenomena occurring over huge areas of the globe a single point measurement is out of the question, which is why meteorologists have resorted to the use of meteorological observing systems and station networks. In order to obtain comparable results from the point measurements of the meteorological network, in addition to a unified observing programme, a degree of uniformity with regard to the measuring instruments' parameters is necessary. Measuring instruments of similar operational characteristics and accuracy should be used with a uniform approach to maintenance and calibration.

The dynamic range of the variability of meteorological variables should be taken into account. Instruments should be as efficient operationally at the Equator as at the poles.

Observing schedules should be the same all over the globe, using a single time scale, that of Greenwich Mean Time (GMT).

All this explains why strict observance of the regulations set out in the various WMO guides on meteorological observations and measurements is necessary.

1.2 Direct and indirect meteorological measurements

Direct meteorological measurements are made by the use of measuring instruments having their sensors at the point of measurement. The instruments themselves may be called direct meteorological instruments and include the more conventional surface meteorological instruments, such as thermometers, hygrometers, barometers, anemometers, etc. Direct meteorological instruments can be used for the measurement of meteorological variables at a distance from the observer and are called remote-reading meteorological instruments.

If a radio link is used for the relay of the meteorological data output of direct meteorological instruments to the human observer, these are called telemetering instruments.

Indirect meteorological measurements are made with the use of either sound or electromagnetic waves. The instruments used, called indirect meteorological instruments, usually measure at a distance. Examples of indirect measuring instruments (or rather measuring systems) are: acoustic radars, lidars (light beam radars), infra-red radiometers, pulse and doppler radars. Indirect measuring instruments open up new prospects of measurement sophistication.

The science dealing with measurement in general is called metrology.

1.3 General - block diagram of a meteorological instrument

All direct measuring instruments, depending on the way they indicate information, may be considered in terms of the following two categories:

(a) Analogue measuring instruments;

(b) Digital measuring instruments.

Meteorological measuring instruments, as a sub-class of measuring instruments, could be considered in terms of the same two categories.

Analogue meteorological instruments give an indication of the measured quantity in a continuous analogue form (analogue = output similar - or analogous - in form to the input). The value of the measured variable is read-out from a suitably-graduated scale of an indicator.

An ordinary thermometer is a typical analogue temperature-measuring instrument. The operator reads the value of the measured quantity to a precision dependent on the graduation of the indicator's scale. In practice, the read-out precision is considered to be limited to half-a-scale division, although an experienced operator would be able to attain a greater precision in reading the scale of the instrument.

The analogue value of the measured quantity can be recorded on paper in the form of a graph against time by a suitable recorder.

A useful representation of an analogue meteorological measuring instrument is a block diagram, considering the instrument as consisting of three functional blocks, as in Figure 1: sensor, signal converter, indicator/recorder.

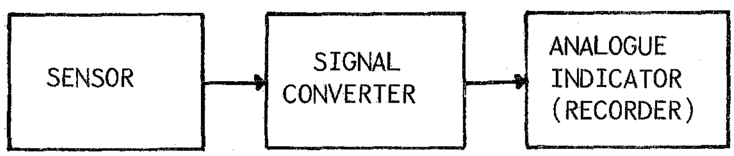


Figure 1 - Block diagram of a measuring instrument - analogue indication

The digital meteorological instrument gives a display of the value of the measured quantity in a discrete, numerical form. The numerical value of the measured variable is indicated on a digital display. The numerical value can be printed out on a paper strip by a digital print-out device. The block-diagram representation of a digital meteorological instrument (Figure 2) considers the instrument as consisting of three functional blocks: sensor, analogue-to-digital signal converter, digital display (digital print-out).

Figure 2 - Block diagram of a measuring instrument - digital indication

The functions of the "blocks" as indicated in Figures 1 and 2 are as follows:

(a) The sensor, common to both analogue and digital instruments, is the functional part of the instrument, which "couples" it to the atmospheric variable measured. Usually, a physical property of the sensor varies with the changes of the measured variable, producing a "signal" at the output of the sensor. With mechanical sensors, the signal may be a simple "elongation" or any mechanical change of the sensor's state. With electrical sensors, the signal may be in the form of a change of electrical resistance or of any other electrical parameter;

(b) The signal converter transforms the signal of the sensor into a different form of signal, suitable for indication by the indicator or recording by the recorder. The signal conversion may sometimes be a simple amplification of the sensor's signal.

The analogue-to-digital signal converter has a similar function with the digital instrument. The analogue signal of the sensor is quantized and converted into a digital form, suitable for indication by the digital display;

(c) The analogue indicator further transforms the signal obtained from the signal converter into a form (usually visual) perceivable by the human operator. The digital display presents the value of the measured quantity in a numerical form (i.e. digits). As an example, one particular type of analogue wind-speed measuring device makes use of a rotational sensor, a cup wheel. The signal converter might be an electrical direct-current generator. Voltage taken from its terminals is applied to a voltmeter indicator.

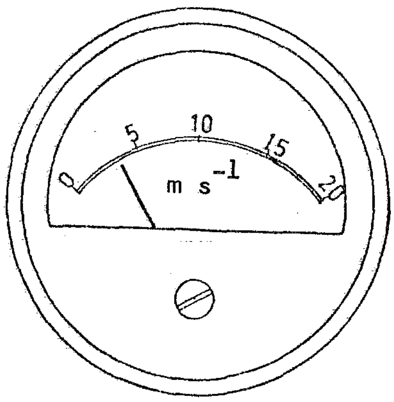


Figure 3 - Analogue indicator of an anemometer

With some analogue instruments, the sensor may have also a signal-converter function. A typical example is the pressure-plate (Wild) anemometer, whose sensor is a heavy metal plate hinged to a horizontal axis. The wind speed, through its pressure on the pressure plate, is converted into an angular deflection of the plate, read out against a scale, i.e. the sensor is a signal converter and an indicator at the same time.

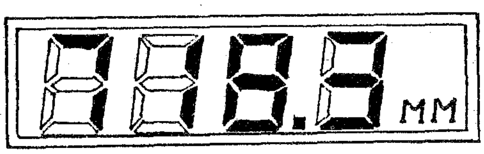


Figure 4 - Barometer seven-segment digital display

With the simple mechanical digital aneroid barometer, the sensor is the pressure capsule, its signal being a mechanical deflection of the membrane. The analogue-to-digital converter is based on a worm-and-cog-wheel device, manually-driven, which converts the deflection of the membrane into a number of revolutions of an axis, to which is coupled the display, a five-digit, reversible revolution counter (see paragraph 2.2.2). An electrical contact indicator is part of the instrument, indicating absence/presence of contact between the membrane and the links of the converter.

A number of recording meteorological instruments are currently in routine use. The following methods of recording have important applications in meteorology:

(a) Ink on paper. An ink-filled pen is moved by the recording mechanism across a paper chart, driven by a clock. The recording is a graph of the measured variable against time;

(b) Scratching pen on wax-paper. A sharp point is moved by the recording mechanism across a wax-paper chart driven by a clock, scratching out the graph of the measured variable against time;

(c) Electrosensitive paper recording. Electrical current is passed by a pointed electrode through electrically-sensitive paper on a revolving clock-driven drum, leaving a trace of the graph of the measured quantity against time;

(d) Spot recording. Colour ribbon prints of the position of the needle of an analogue microammeter indicator, on a clock-driven paper-strip chart are obtained by this method. The trace, a dotted line, is a graph of the measured quantity against time;

(e) Digital print-out. Numerical values of the measured quantity are printed on a paper strip at regular time intervals. The time of the print-out is usually indicated in a four-digit form (hours and minutes) beside the value of the measured quantity.

The methods of recording listed above are in use for routine surface meteorological observations at manned stations. In addition, the use of telegraph-code punched paper tape or magnetic-tape binary-code recording may be considered at automatic weather stations. A number of other recording methods of lesser importance are also used in meteorology.

Many of the recording instruments used in the meteorological network are of the mechanical sensor type in which the deflection of the free end of a sensor is magnified by levers, activating a pen arm. The pen, filled with ink, leaves a trace on a paper chart, wound on a clock-driven drum. Because of the very small power of the sensor, such recorders should be as free from friction between the moving parts, as well as between pen and paper, as possible. Recorders of the type described are usually provided with means for making time marks on the chart.

The paper chart is made of specially treated paper, in order to achieve a well-defined and legible trace, with no ink-blots or disruptions and the ink used is a slow-drying, freeze-resistant type.

Clocks in recording instruments used in routine operational work may be fixed inside the drum and revolve with it or fixed to the chassis of the instrument, in which case only the drum rotates. The latter type has more advantages and it is easier to eliminate "backlash" (play of the drum in direction of rotation, due to unavoidable play in the gears of the clock), which is one source of time errors in the recording. Clocks are provided with a clock-rate adjustment device.

Recording instruments of this type should be compared regularly with direct-reading instruments.

1.4 Dynamic behaviour of measuring instruments - first-order measuring instruments - second-order measuring instruments - general features of meteorological instruments

The response of meteorological instruments to a sudden change of the measured variable is not instantaneous. Generally speaking, an instrument needs some "settling time" in order to indicate the new value of a meteorological variable which has undergone a step-change. This change is known as a "step-forcing function" and the response of the measuring instrument during its settling time as its "transient response".

According to their dynamic behaviour and transient response, meteorological instruments fall into two groups: first-order measuring instruments (systems) and second-order measuring instruments (systems).

First-order measuring systems, when subjected to a step-forcing function, have their output (indication for the measured variable) moving towards the forcing-function value, as a function of the input (the forcing-function value) and the first derivative of the output (the rate of change of the output). The transient response of this group of instruments is illustrated in Figure 5: the instrument's output is approaching the forcing-function value following an exponential law - faster at the beginning, but gradually slowing down, approaching the forcing-function value asymptotically. The time co-ordinate is in time-constant units, one time constant being the time necessary for the output to reach 63 per cent of the forcing-function value. In practice, a time equivalent to more than five time constants is necessary for the output almost to reach the forcing-function value (see paragraph 3.4).

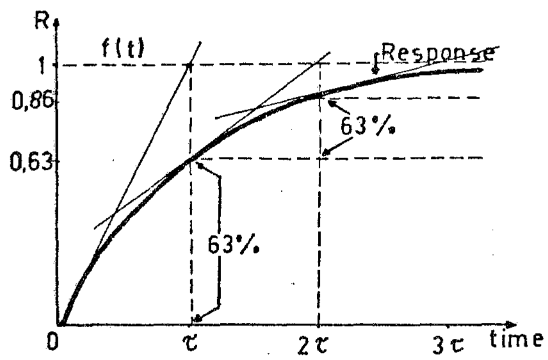


Figure 5 - Response of a first-order measuring instrument

Instruments belonging to the group of second-order measuring systems have their output moving towards the forcing-function value, according to the input and first and second derivatives of the output (rate of change and acceleration). There is a tendency for fading-out oscillations about the forcing-function value with such measuring systems. The frequency and amplitude of these oscillations are a function of the damping of the measuring system. The dynamic behaviour of second-order systems is described by an entity called the "damping ratio", ξ, which is the ratio of the actual damping present in the system to the critical damping (one which produces no overshoots). With $\xi < 1$, the system tends to oscillate with an amplitude decreasing with time when subjected to a step-forcing function.

If $\xi = 1$, the system behaves similarly to first-order systems: aperiodic settling. For $\xi > 1$, the system is overdamped and has an aperiodic response, sluggish in character, depending on the actual value of the damping ratio (Figure 6).

Damping of mechanical systems is caused by friction. Second-order transient response can be a problem with some meteorological instruments, e.g. wind vanes. Damping close to the critical value improves wind-vane accuracy.

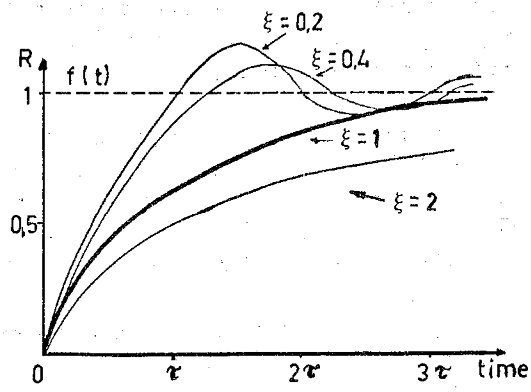


Figure 6 - Response of a second-order measuring instrument

Much attention has been paid to the settling time of meteorological instruments, because of its importance to measurement. There are, however, other important features of instruments which will be briefly discussed and defined:

Accuracy is one such important feature. An instrument is accurate if its response is compatible with the scale of its standard of calibration and the response is reproducible. The more accurate an instrument, the closer are the measurement results to the "true value" of the measured quantity.

Sensitivity is another important feature. Sensitivity of a measuring instrument could be defined as the ratio of the change of output to the change of input (the variable measured). There are fixed requirements, as regards different categories of meteorological instruments. An instrument with a sensitivity lower than that required would miss important measurement detail, while hypersensitive instruments would record unnecessary detail (e.g. a hypersensitive barograph would record pressure fluctuations caused by the opening and closing of a door).

Specificity of response: an instrument has a good specificity of response if it is insensitive to all variables except the one that it is designed to measure. If shielded from precipitation, the mercury thermometer is virtually insensitive to changes in air humidity or pressure. Its specific response is to changes in temperature, while the aneroid barograph's pressure readings are affected by changes in temperature. It has an inferior specificity of response compared with the shielded thermometer.

Linearity of response: an instrument has linear response if its output is a linear function of the input (the calibration "curve" is a straight line). Linearity is a desirable feature of the meteorological instrument, enabling fast and accurate interpolation between two adjacent scale divisions.

Requirements concerning meteorological instruments' accuracy, sensitivity, linearity of response and transient response are subject to standardization. The reason behind this is the desired comparability of measurements made by different types and makes of instruments.

Instruments used for operational purposes (meteorological network instruments) should be designed in a way to make them durable and convenient in operation.

Reliability of meteorological instruments is an important factor. They should be designed in such a way that they function with as low a rate of failure and break-down as possible.

A statistical approach to instrument and equipment failure gives an interesting picture of the "failure rate", λ - an instrument-reliability parameter. The failure rate/time curve shown in Figure 7 reveals three definite time intervals; in each one of them the failure rate, λ, has a different character: I - interval of "inborn defects", λ on the decrease with time; II - interval of a constant failure rate; and III - interval of the wear-out failures, λ on the increase with time. The time interval II is the useful operational life-span of the instrument or equipment. The reliability of the instrument, as far as time interval II is concerned, is expressed as a function of failure rate and time as follows:

$$R(t)=e^{-\lambda t}$$

The mean time between failures (MTBF) is also a function of λ:

$$\text{MTBF} = \frac{1}{\lambda}$$

Reliability figures and reliability parameters of a complex piece of equipment can be obtained as functions of the corresponding parameters of the components of the equipment.

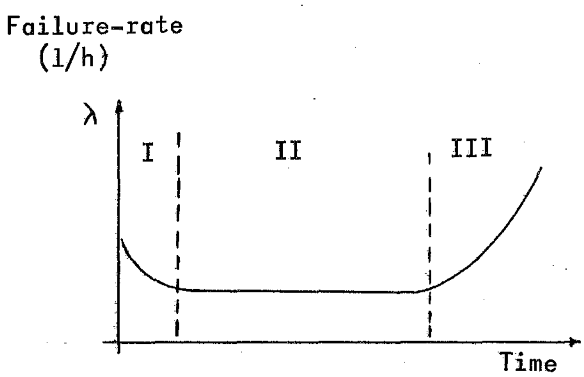


Figure 7 - Failure rate versus time

1.5 General requirements for siting and exposure of meteorological instruments - the meteorological shelter

Surface meteorological instruments are installed on the site of a meteorological observing station. A plot of level ground, usually measuring 6 by 9 m and covered by short grass, provides satisfactory conditions for the outdoor installation of meteorological instruments.

The site of the meteorological station should be meteorologically representative of the area in which it is located, i.e. the atmospheric variables measured on the site should be typical of the area. A site which has obstructions in the near vicinity which might affect the variables being measured should be avoided, if possible. Large buildings and artificial heat, humidity or pollution sources are likely to distort the measurements of temperature, humidity, evaporation, wind, etc. As far as practicable, meteorological instruments' sites should be away from steep slopes, cliffs and hollows.

One of the general rules, as far as the exposure of instruments is concerned, is that it should conform to WMO recommendations (see The Guide to Instruments and Methods of Observation - WMO-No.8). This is another prerequisite for comparability of meteorological data coming from different stations.

For outdoor meteorological measurements of temperature and humidity, the instruments should be installed inside a shelter or screen so as to avoid the effects of direct solar radiation and adverse weather.

The meteorological shelter should be designed in such a way as to minimize the harmful effects of weather on the instruments, while ensuring the same meteorological conditions as those of the air outside. The Stevenson screen is a meteorological instrument shelter in widespread use. Generally, the shelter is a box, made of a low heat-conductivity material (wood), large enough to accommodate the meteorological instruments and having double louvred walls which enable good ventilation, while minimizing the effects of radiant heat. For the same purpose, the roof is made of two layers of wood with an air layer for thermal insulation and the floor is made of overlapping boards for good ventilation. The shelter is painted white inside and out. The door of the shelter opens in such a way as to prevent the observer from coming too close to the meteorological instruments and affecting them by his body heat. The orientation of the shelter is such that the direct illumination of the instruments by the Sun, with the door open, is not likely to occur (Figure 8).

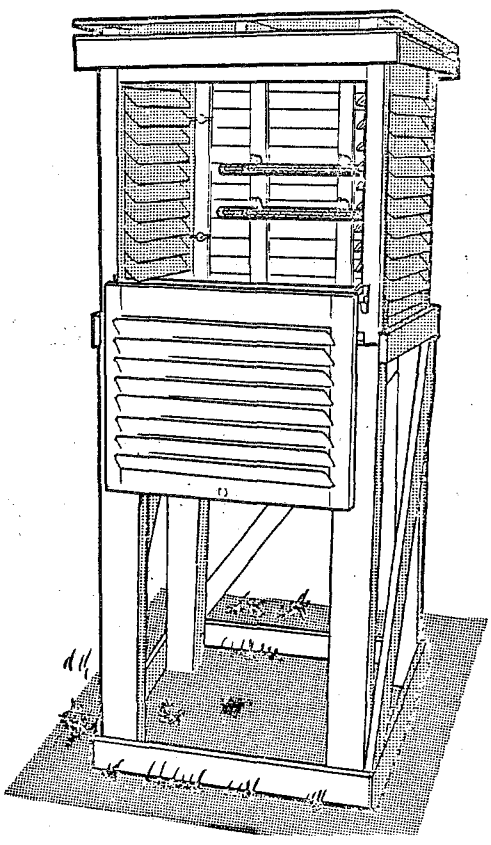


Figure 8 - Thermometer shelter

The screen is mounted at such a height that the thermometer bulbs are 1.25 – 2 m above the ground. The screen's support should be strong enough to prevent vibrations caused by the wind. Meteorological screens for use in the tropics and polar regions are of slightly different designs, allowing for the difference in conditions (height of the Sun above the horizon, continuous and deep snow cover, etc.). At high mountain stations with heavy snowfall, meteorological screens are provided with supports which are extendable in height enabling the screens to be kept at the prescribed height above the snow surface.

The best lighting for the meteorological shelter is a low-power luminescent lamp installed inside the screen near its roof. The other alternative is lighting from outside.

Meteorological shelters need to be cleaned frequently and repainted every year.

CHAPTER 2

MEASUREMENT OF ATMOSPHERIC PRESSURE

2.1 Nature of atmospheric pressure - units of measurement

The Earth's gaseous atmosphere, by virtue of its weight, exerts a pressure on the Earth's surface. The pressure is equal to the weight of a vertical column of air of unit cross-section area above the Earth's surface, extending to the outer limits of the atmosphere. The existence of atmospheric pressure was first demonstrated by Torricelli (1643). Until the invention of the so-called aneroid barometer (1848), the mercury barometer was the only practical instrument for atmospheric-pressure measurements.

The mercury column of the barometer remains in equilibrium with the air column. Changes of atmospheric pressure result in changes in the length of the mercury column, this being the traditional reason for the use of a barometric scale graduated in millimetres or inches of mercury. The length of the mercury column depends on other factors such as temperature and the force of gravity, in addition to atmospheric pressure. This leads to the definition of the so-called standard conditions of pressure measurement. As standards, a temperature of $0^{\circ}C$ (density of the mercury 13.5951 g cm^{-3}) and an acceleration as a result of the force of gravity g_a = 9.806 65 m s^{-2} are accepted. It should be noted that g_a is not the value of gravity at latitude 45° and sea-level.

In meteorology, atmospheric pressure is reported in hectopascals (hPa). 1 hPa = 100 Pa, the pascal being the basic S.I. unit of pressure.

$$\text{Since } 1 \text{ Pa} = 1 \text{ N m}^{-2}$$
$$1 \text{ hPa} = 100 \text{ N m}^{-2}$$
$$\text{Since also } 1 \text{ mb} = 100 \text{ N m}^{-2},$$
$$1 \text{ hPa} = 1 \text{ mb}$$

As already mentioned, the units millimetre and inch of mercury although not in general use for atmospheric pressure are still in circulation. A conversion table for the various pressure units (assuming standard conditions) is given below:

1 hPa = 0.750062 mm = 0.02953 in.Hg
1 mm = 1.333224 hPa = 0.03937008 in.Hg (1 inch = 25.4 mm)

Under standard conditions, a column of mercury of 760 mm exerts a pressure of 1 013.250 hPa, which corresponds to 10 322.92 kg m^{-2}.

2.2 Principles underlying the operation of atmospheric-pressure measuring instruments

As already mentioned in connexion with the mercury barometer, the pressure of the atmosphere is balanced against the weight of the mercury column. The weight of the column may be weighed on a special balance or by a known cross-section of the column, read-out in equivalent pressure units directly from a scale measuring the length of the column.

The pressure of the atmosphere may be balanced against a spring-loaded membrane of an evacuated metallic capsule. A change in the atmospheric pressure causes a deflection of the membrane. The membrane deflection, suitably magnified, may be read-out from a scale graduated either in millimetres or hectopascals. This is the principle of the aneroid barometer.

The boiling temperature of a liquid depends on the atmospheric pressure. At a given temperature, the vapour pressure of the liquid comes into equilibrium with the atmospheric pressure and the liquid begins to boil. The relationship between the boiling temperature of the liquid and the corresponding atmospheric pressure makes possible the measurement of the latter. This is the principle of the hypsometer.

The above three principles of atmospheric pressure measurement are fundamental to the use of meteorological pressure instruments.

2.2.1 Mercury barometers - Fortin and contracted-scale types

Essentially, the mercury barometer consists of a vertically-mounted glass tube, sealed at the top, filled with mercury and having its open lower end dipping into a cistern half-filled with mercury. The atmospheric pressure acting on the open mercury surface in the cistern balances the weight of the mercury column in the barometric tube. The tube is long enough to allow for the change in height of the mercury column in it, following the changes of atmospheric pressure. The height of the mercury column is measured by a scale attached to the tube. Since temperature affects both the mercury column and the scale, a thermometer is attached to the barometer's scale, the temperature readings being used in the temperature correction of the pressure.

Probably the two most common types of mercury barometer are the Fortin and the contracted-scale barometers.

The Fortin barometer answers the description of the mercury barometer already given above. There are a few details, however, which need further discussion.

The cistern of the Fortin barometer (Figure 9) consists of three main parts: leather bottom with a screw to adjust the level of cistern mercury, glass-tube cistern wall, cistern top with fiducial point (ivory spike, whose point is used as a reference datum level, indicating the zero of the barometer's scale). The cistern parts are held together by bolts and the mercury in the cistern is kept away from the metal parts by means of box-wood bushes, as mercury forms amalgams with some metals (brass, alloy, silver, etc.). A tiny hole in the cistern top, provided with a screw, is the only inlet for atmospheric air into the cistern.

The cistern is fixed to a slotted metal tube which carries the barometer scale and the attached thermometer. The metal tube acts as a protection for the glass barometer tube.

The precise height of the mercury column is estimated by means of a vernier scale mounted in the slot in the upper part of the metal tube. The vernier scale is moved relative to the main scale by a micrometer.

The protective, slotted metal tube is provided at its upper end with a metal hook for hanging the barometer on a wall.

The vernier is a part of all the mercury barometers under consideration here. In essence, it is a movable, additional scale, capable of being slid into position along the main scale in such a way that its lower edge visually "touches" the image of the mercury meniscus, seen through the slot of the protective tube.

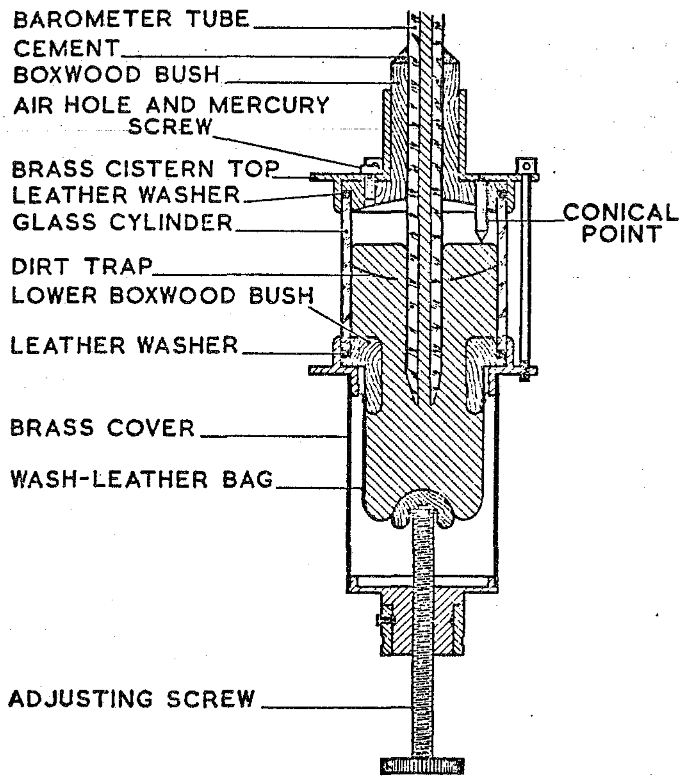


Figure 9 - Cistern of a Fortin barometer

Generally speaking, the vernier has n scale divisions of its own, the total length of all n of them corresponding to the length of (n-1) main-scale divisions. In this way the vernier scale division differs from one main-scale division by 1/n of a main-scale division.

When reading the barometer, the lower edge of the vernier scale (the zero scale division) is brought into visual contact with the top of the mercury column meniscus. If the vernier zero is found to lie between two main-scale divisions, note is taken of which vernier-scale division is coincident with a main-scale division. The numerical value of this vernier-scale division represents the fraction of one main-scale division by which the vernier zero lies above the next main-scale division immediately below the vernier zero.

For example, let us assume the vernier has 10 scale divisions with a total length of nine main-scale divisions. Further let us assume the vernier zero is between 753 and 754 mm on the main scale, while the vernier's sixth division is coincident with one of the main-scale divisions. Then the atmospheric pressure to be read out on the scale is 753.6 mm, as there are six-tenths of the 754th main-scale division above 753 mm.

Besides a 10:9 ratio of vernier-/main-scale divisions, there are other ratios as well: 20 vsd = 19 msd, or 50 vsd = 49 msd. In each case the vernier-scale division is smaller than one main-scale division by 1/nth vernier-scale division (n = number of vernier-scale divisions). This in fact indicates the accuracy of the reading attainable: 1/10, 1/20 = 0.05 or 1/50 = 0.02 mm or hPa correspondingly.

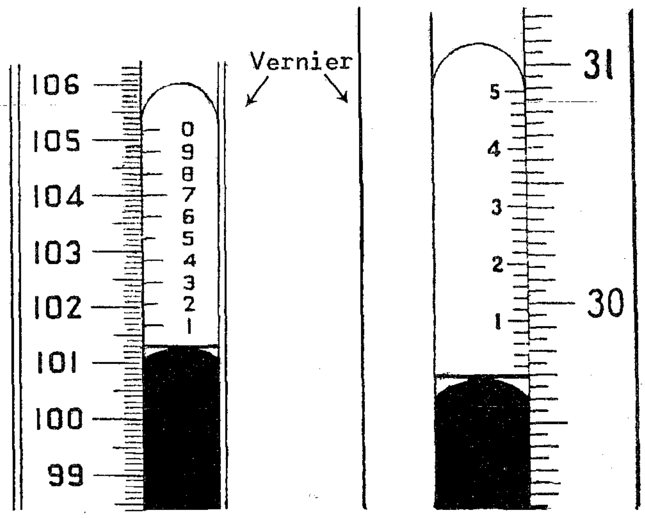


Figure 10 - Barometer vernier

A reading of the Fortin barometer is executed in five steps:

(1) Take a reading of the attached thermometer to the nearest 0.1°C and write it down;

(2) Using the bottom screw, adjust the level of the mercury in the cistern so as to just touch the fiducial point (observe the ivory point's image in the "mirror" of the mercury surface in the cistern);

(3) Gently tap the barometer tube with your forefinger to remove any mercury sticking to the glass-tube wall. Check the level and if necessary repeat step (2);

(4) Keeping your eye level with the mercury meniscus in the tube, bring the vernier's zero edge into visual contact with the top of the mercury column;

(5) Read the atmospheric pressure to the nearest 0.1 hPa (or mm, depending on scale) and write this down.

Special attention should be given to step (4) of the reading procedures: the vernier's zero edge should neither "cut off" the top nor leave a gap above the meniscus of the mercury column. The zero line should look like a tangent to the uppermost point of the meniscus.

The barometer's readings should be reduced to standard conditions. For the barometer readings, made at different stations, to be comparable, the following corrections should be made:

(a) Correction for index error

This is a correction determined through a comparison between the barometer and a standard instrument. The correction is stated in the certificate of the barometer. With good barometers, it should not exceed a few tenths of a hectopascal;

(b) Correction for temperature

$$C_t = \frac{-B(a-b)t}{1+at}$$

where:

C_t = correction at temperature, t^o;

a = coefficient of cubic expansion of mercury;

b = coefficient of linear expansion of scale;

B = observed barometer reading at t^o.

Substituting for the expansion coefficients (brass scale assumed):

$$C_t = 0.000163\ B.t$$

(c) Correction for gravity

$$B_n = B_1 \frac{g_{\varphi h}}{g_n}$$

where:

B_n = barometer reading reduced to standard gravity and standard temperature and corrected for index error;

B_1 = barometer reading reduced to standard temperature and corrected for index error;

$g_{\varphi h}$ = local acceleration due to gravity (cm s^{-2}) at a station at latitude φ and elevation h above sea-level;

g_n = standard gravity acceleration (980.665 cm s^{-2}).

The contracted scale barometer is more convenient in operation. The cistern has no leather-bag bottom and there is no adjustment for the level of mercury in the cistern. The scale of the barometer, which in all other respects looks like the Fortin barometer, is compensated for changes in the level of the mercury in the cistern.

The following is a discussion of the rationale behind the contraction of the scale divisions:

Let us consider the response of the barometer to a change of pressure in a one-millimetre column of mercury and find out the value of one scale division of the contracted scale.

Assuming the pressure change causes a change (e.g. an increase), y, in the meniscus height in the mercury tube and a corresponding change (decrease), x, in the mercury level inside the cistern, the following relationship will hold:

$$x + y = 1 \text{ mm} \quad \ldots\ldots \tag{1}$$

Obviously, the change in the cistern volume, V_1, equals the change in the tube volume, V_2:

$$V_1 = \pi R^2 x - r_1^2 x \qquad (2)$$

$$V_2 = \pi r^2 y \qquad (3)$$

but

$$V_1 = V_2 \qquad (4)$$

therefore

$$x = \frac{y\, r^2}{R^2 - r_1^2} \qquad (5)$$

Substituting equation (5) in equation (1) yields:

$$y = \frac{R^2 - r_1^2}{R^2 - r_1^2 + r^2} \qquad (6)$$

Obviously, if the scale division of the barometer is contracted to the value of y from (6), while reading it as 1 mm, there will be no need for an adjustment of the cistern level.

With one specific make of barometer, having a millimetre scale, the contracted scale division is y = 0.980 mm.

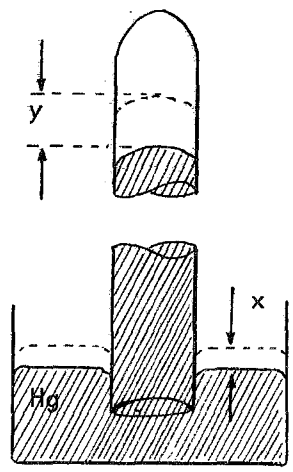


Figure 11 - Barometer tube and cistern - x/y relationship

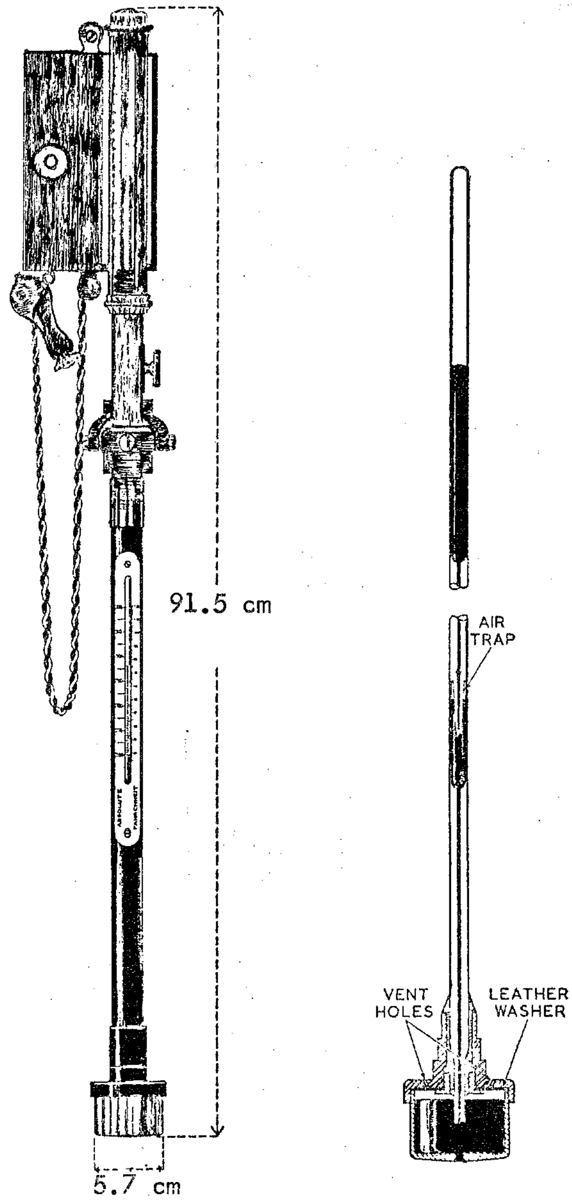
Calculations for the hectopascal contracted scale can be made in much the same way. Reading of the contracted-scale barometer is carried out in four steps:

(1) Take a reading of the attached thermometer to the nearest 0.1°C and write it down;

(2) Using the forefinger, gently tap the barometer's tube to remove any mercury sticking to the tube wall;

(3) Bring the vernier's zero edge into visual contact with the mercury column meniscus, while keeping the eye level with it;

(4) Read the vernier scale to the nearest 0.1 hPa and write this down.



with illuminator section view

Figure 12 - Contracted-scale barometer

The pressure read-out should be corrected for index error and standard conditions.

Temperature correction is made using the following formula:

$$C_t = \frac{B(a - b)t}{1 + at} - 1.33 \frac{V}{A} (a - 3n)t$$

where:

C_t = correction at temperature, t^o;

a = coefficient of cubic expansion of mercury;

b = coefficient of linear expansion of the scale;

n = a linear expansion coefficient representing chiefly the expansion of the iron cistern and the glass tube;

B = observed barometer reading at temperature t^oC;

V = total volume of mercury in the barometer in mm^3;

A = effective area of cistern in mm^2.

Putting a = 0.0001818, b = 0.0000184 per 1°C and n = 0.000010 per 1°C and substituting in the above formula yields the correction for brass scales:

$$C_t = - 0.000163 \left(B + 1.24 \frac{V}{A}\right)t$$

The correction for gravity is made using the formula already discussed on page 18 in connexion with the Fortin barometer.

The main sources of error, with regard to mercury barometers are as follows:

(a) Effect of wind

Dynamical fluctuations of pressure may be superimposed on static pressure in conditions of strong and gusty winds, depending on the wind direction and the local environment in which the barometer is situated. Fluctuations can amount to two or three hectopascals. Under such conditions, the use of a so-called static pressure head may be a remedy (Guide to Meteorological Instruments and Methods of Observation (WMO-No. 8);

(b) Effect of temperature stratification in the barometric room

With no ventilation in the barometric room and under certain conditions, temperatures at the barometric thermometer's reservoir and at the upper part of the barometer may be different, owing to temperature stratification of the air inside the room.

A small electric fan can prevent such conditions from arising. The fan should be switched off while reading the barometer, because of possible dynamic pressure variations;

(c) Presence of gas or vapours in the barometer's Torricellian vacuum

A perfect vacuum is assumed above the mercury column inside the barometric tube (Torricellian vacuum). The presence of small amounts of gas (air) can be detected by a dull click being heard whenever the barometer is inclined. The normal click, which is sharp and metallic-sounding, means that the mercury column has reached the sealed end of the glass tube without meeting any obstruction from compressed gases. When performing this test, the operator should be aware of the danger of breaking the barometer tube by inclining the barometer too quickly.

Water vapour cannot be detected in this way, because it is condensed by compression.

Marked deviations in the read-out of the barometer warrant a comparison against a standard instrument with an eventual refill or replacement of the barometer tube.

Mercury vapour does not affect the accuracy of the measurement because of its negligible pressure value: 0.00399 hPa at 30°C.

(d) Effect of capillary depression

With small-bore barometer tubes, the surface tension of mercury may cause an appreciable depression of the mercury column. The effect is demonstrated by the table below:

Internal diameter of barometer tube	Absolute value of depression (average angle of contact = 35°)
0.20" = 5.1 mm	0.046" = 1.56 mm
0.30" = 7.7 mm	0.023" = 0.73 mm
0.40" = 10.3 mm	0.011" = 0.37 mm
0.50" = 12.9 mm	0.006" = 0.20 mm
0.60" = 15.5 mm	0.003" = 0.10 mm

(e) Deviation from the vertical position of the barometer

The effect of barometer tilt (contracted scale) can be evaluated from the relationship:

$$B = B_t \cos t$$

where:

B = read-out of the vertical barometer;

B_t = read-out of the tilted barometer;

t = angle of the barometer tilt.

As a rough criterion, a departure from the lowest point of the barometer from the vertical position of 12.3 mm will cause a pressure reading about 0.133 hPa too high.

The Fortin barometer is more sensitive to tilt: with a fiducial point in the cistern about 12 mm away from the barometer's axis, a displacement of the cistern of about 1 mm from the vertical may cause an error of 0.666 hPa.

(f) Effect of dirt, oxidized mercury

Impurities of all kinds, as well as dissolved metals in the barometer's mercury are a source of error in pressure measurements. Oxidized mercury has an appreciably higher capillary depression and the barometer would read lower pressure values.

In calibration against a standard barometer the following tolerances for a station barometer should not be exceeded:

(1) Maximum permissible error at about 1 000 hPa .... ± 0.3 hPa

(2) Maximum permissible error at any other pressure for a barometer whose range:

(a) Does not extend below 800 hPa .... ± 0.5 hPa

(b) Extends below 800 hPa .... ± 0.8 hPa

Difference between errors over an interval of 100 hPa or less should not exceed .... ± 0.3 hPa

(3) For a marine barometer the error at a point should not exceed .... ± 0.5 hPa

(Guide to Meteorological Instruments and Methods of Observation, WMO-No. 8, 5th edition, paragraph 3.2.1)

2.2.2 Aneroid barometers - analogue and digital read-out - the barograph

The sensor of the aneroid barometer is a circular metal capsule, either evacuated to a vacuum of 10^{-2} mm or filled by an inert gas at low pressure (50 mm). The material of the capsule should have excellent elastic properties. Copper-beryllium, nickel-beryllium, nickel-titanium-beryllium or a steel alloy are used for this purpose. Vacuum capsules have a steel spring inside to prevent them from collapsing under atmospheric pressure.

The thin wall (0.2 mm) of the capsule is circularly corrugated, the corrugation troughs and peaks spaced a few millimetres apart. In fact, the capsule is made of two corrugated diaphragms, soldered or electrically welded together. The corrugation of the diaphragms improves the elastic properties of the capsule and its linearity of response to changes in atmospheric pressure. With decreasing atmospheric pressure the capsule expands, its central part having the maximum deflection. The following relationship holds for the deflection of the capsule's diaphragm as a function of the pressure:

$$\Delta f_c = \frac{R^4}{5.87 \; h^3 \, . \, E \, (1 + 0.2 \, f_m/h^2)} \Delta P$$

where:

Δf_c = deflection of the central part of the diaphragm;

ΔP = atmospheric pressure change;

R = working radius of the capsule;

h = thickness of the diaphragm wall;

f_m = maximum deflection of the diaphragm;

E = module of elasticity of the diaphragm alloy.

The deflection force, which can be considered as being applied at the centre of the diaphragm, can be calculated from the relationship:

$$F = PA_o$$

where:

P = pressure;

A = total area;

A_o = membrane effective area: $1/3 < A_o/A < 1$.

The approximate pressure range of the aneroid capsule can be determined through the maximum deflection f_m using the empirical expression: $f_m \leq 5\%$ R and the relationship between Δf_c and ΔP_o^m

As an atmospheric-pressure sensor the aneroid capsule is inferior to the mercury barometer, chiefly in respect to the stability of calibration characteristics but it is more durable, portable and compact and far less senstive to shock.

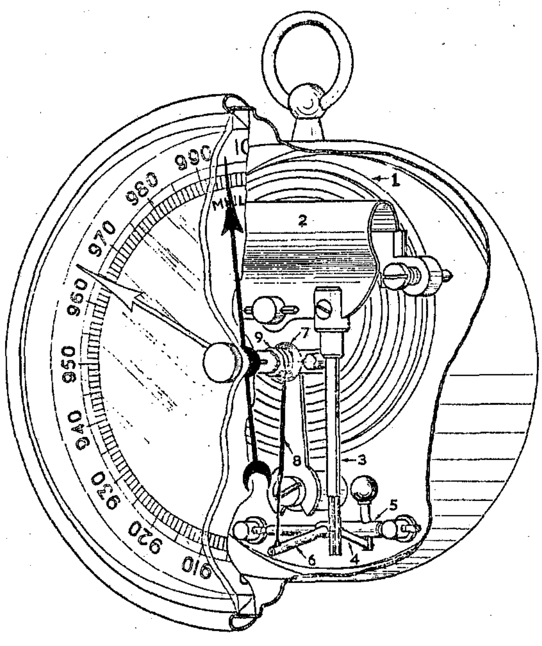


Figure 13 - Typical mechanism of an aneroid barometer

Signal convertors for the pressure capsule, used with analogue read-out aneroid barometers are usually a mechanical type (Figure 13). The action of the mechanism is as follows:

With atmospheric pressure falling, the diaphragm of the capsule (1) expands, causing the leaf-spring (2) to relax and move the arm (3) upward. This arm, through the connecting link (4) rotates the rocking-bar (5), which in turn, through the arm (6), the arbor chain (8) wound upon the pulley (9) contracts the hairspring (7) and thus turns the pointer towards decreasing pressure values on the dial. The screw in the base-plate enables the position of the carriage to be adjusted, thus altering the zero position of the pointer.

This type of signal converter performs two chief functions: amplification of the signal (the deflection of the diaphragm) and transformation of the linear deflection into a rotational motion of the axis of the pointer. The main disadvantage of the mechanical signal converter is the presence of mechanical friction, acting against the deflection force of the aneroid capsule.

Good instruments of this kind are provided with a bimetallic thermocompensating link (incorporated in the arm (3)), thus compensating for the effects of temperature changes. With such an arrangement, it is possible to keep the scale error at any point less than 0.5 hPa.

Aneroid barometers have certain advantages over mercury barometers but they are considered secondary instruments needing a check against a mercury barometer at least once a year.

If adjusted to read the pressure at the actual elevation of the site of measurement and thermocompensated, the aneroid barometer does not need any correction (including for gravity), except instrumental correction.

The sources of error for the aneroid barometer are:

(a) Incomplete compensation for temperature changes

With increasing temperature and worsening of the elastic properties of the capsule, the instrument tends to read too high a pressure. A well-designed bimetallic compensator can control the temperature error over the whole range of measured pressure values.

Partial compensation is attained through the presence of inert gas in the aneroid capsule, as it is fully valid at only one pressure;

(b) Hysteresis

If the aneroid capsule is subjected to a large and rapid change of pressure, which is then brought back to its initial value, the capsule will indicate a different initial pressure which will change slowly until it reaches its true original value. This phenomenon is called hysteresis;

(c) Secular changes of the elastic properties of the aneroid capsule

Because of gradual material structural changes, the elastic properties of the capsule eventually deteriorate, leading to errors which increase with time. If a measurement accuracy better than 0.2 hPa is desired, a monthly check of the aneroid barometer against a standard instrument is advisable.

Digital aneroid barometers make use of the same aneroid capsule pressure sensor as the one described above. The main advantage of the modern digital instrument is that its capsule is not loaded by the friction of the mechanical signal converter, thus enabling a higher accuracy and greater reproducibility of results.

One electromechanical analogue-to-digital converter is shown in Figure 14.

The deflection, f, of the barometer capsule (1) is transmitted to the arm (6) with a total length of $L_1 + L_2$, mechanically amplified and appearing as F at its end, a silver contact tip. This silver contact tip is restricted between the contact-fork tips (only a few micrometres of free play) of the tracking device (13), which moves up and down along the parallel rod (14), actuated by the tracking screw (5). The tracking device moves in such a way as to break contact with the arm (6), leaving its contact tip in the middle of the gap between the tips of the contact fork. If, for example, electrical contact is established between the arm tip and the lower contact tip of the fork, the electric motor (12) is set in motion in the proper direction and through its gear (10) and (11) and the worm (9) and cog-wheel (8) arrangement, makes the tracking screw turn and shift the tracking device with the contact fork downwards until contact is broken. If the upper contact is actuated, the same process is started, only in the opposite direction.

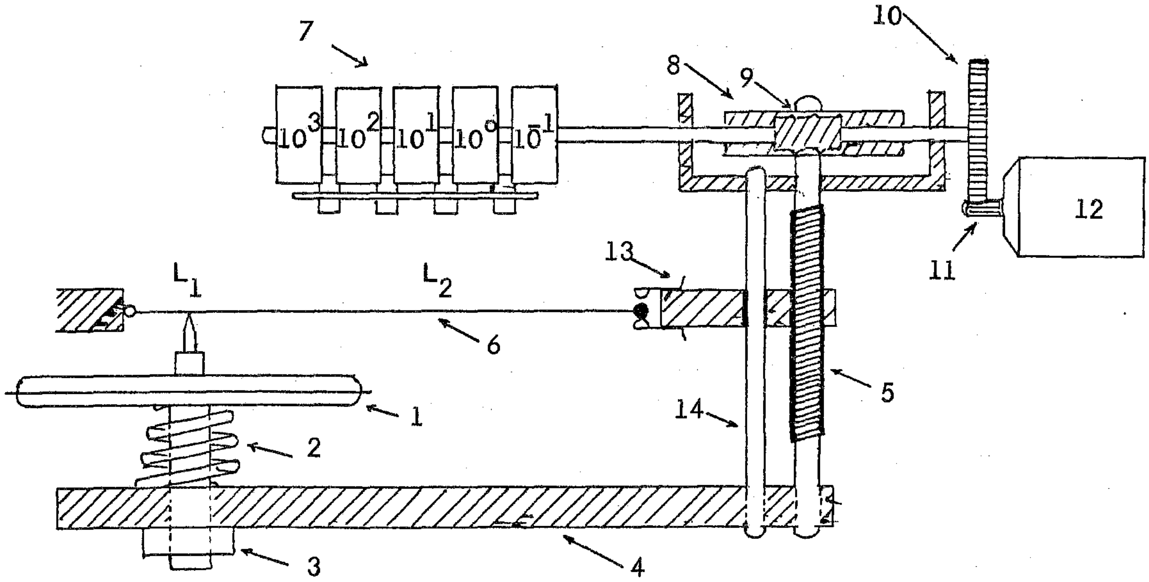


Figure 14 - Example of an electromechanical analogue-to-digital converter for an aneroid barometer

The axis carrying the worm (9) is connected to the axis of a reversible five-digit counter. The linear deflection of the tip of the arm (6) is converted into a number of revolutions of the counter's axis, which is displayed by the counter itself. If the revolutions of the tracking screw (5) are N for a change of pressure ΔP, the revolutions of the counter's axis N_c should be related to ΔP through the relationship:

$$N_c = \frac{k \cdot \Delta P(L_1 + L_2)}{\gamma \cdot s \cdot L_1}$$

where:

L_1, L_2 = as indicated above in Figure 14, arm (6);

s = pitch of the thread of the tracking screw;

k = $\Delta f / \Delta P$;

Δf = deflection of the capsule's diaphragm;

ΔP = pressure change, which caused the deflection, Δf;

γ = N/N_c.

With the above relationships valid for the gears, the counter should display the actual value of the atmospheric pressure.

The electric motor is switched on and off in either one or the other direction by the contact assembly, through an electronic servo package, shown in Figure 15. Terminals marked by 1 and 2 are connected to the "barometric tendency" display.

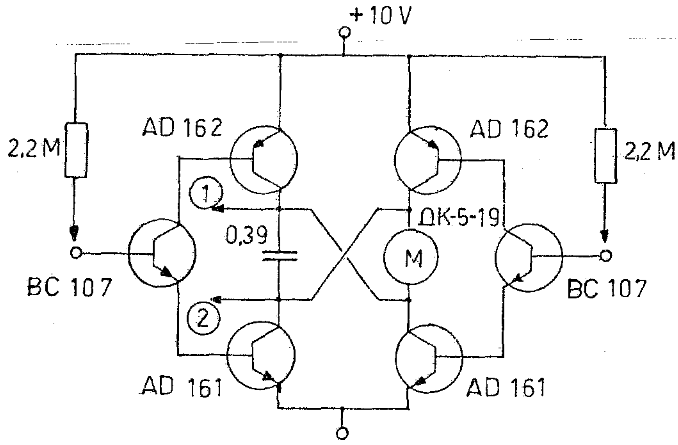


Figure 15 - Servo system of a digital aneroid barometer

Based on a similar principle, there are also manually-actuated analogue-to-digital converters, using a light indicator for the "contact on/contact off" positions of the tracking device.

A fully electronic, solid-state device, with a sensor kept in a thermostatic chamber, competes in accuracy with the high-precision mercury barometer, but it can be used only as a secondary standard.

The station barograph is a recording aneroid barometer. A stack of barometric capsules, connected in series is used as the pressure sensor of the barograph, capable of giving a greater deflection by the same pressure change.

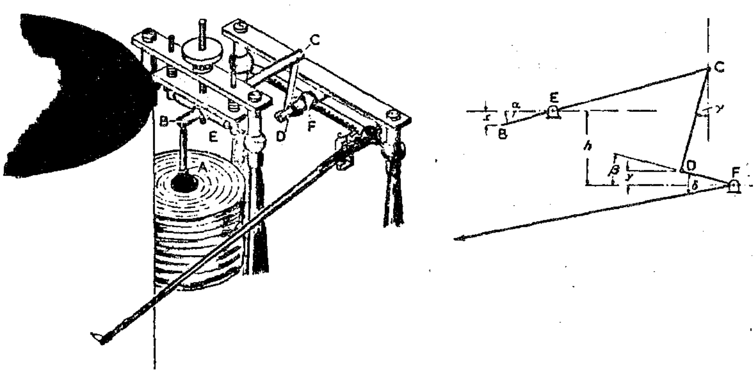


Figure 16 - Lever system of open-scale barograph

A system of levers can amplify the deflection by 100. This enables a chart recording with a pressure range of 100 hPa and scale divisions of at least 1 mm, equivalent to 1 hPa. The chart, known as a barogram, has time-scale divisions of 2 or 3 hours, or 10 or 15 minutes for weekly or daily charts respectively. The barogram is wrapped round a clock-driven revolving drum.

With such an arrangement, the pen arm has a full-scale deflection of 100 mm and at all points of the recording the pen should exert equal pressure on the paper chart, in order that a good-quality, uninterrupted recording is obtained. This is not easy to attain by a spring-loaded pen arm, because the pen is travelling along a segment of a circle between the two extreme positions of the pen arm, while the chart surface is cylindrical, having the curvature of the clock drum.

The solution is the so-called gate suspension for the pen arm. The pen arm (A) is hinged to the rocking bar (B) of the lever system and is capable of pivoting about an axis departing slightly from the vertical position in such a way as to make a component of the pen arm's weight keep the pen pressed to the paper (Figure 17).

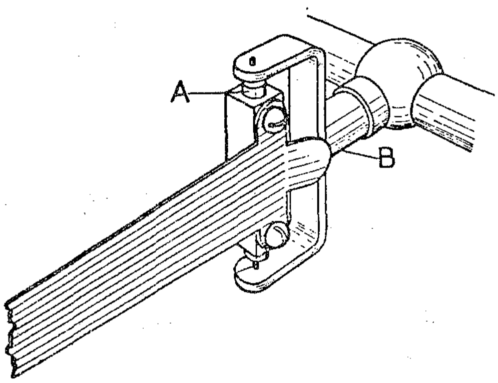


Figure 17 - Gate suspension

A number of pen types are shown in Figure 18. The types marked (a) and (e) are in widespread use with all kinds of mechanical recording instruments.

With electronic recording instruments, the fibre-glass tip recording pen has been found more suitable.

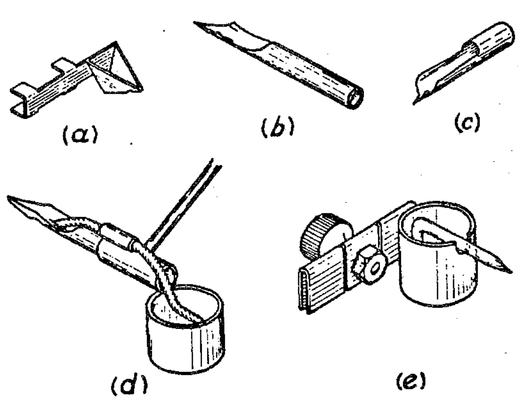


Figure 18 - Pens

Care should be taken with the recording mechanism of the barograph. When changing the paper chart, the pen arm should be handled gently, avoiding bending or twisting.

The pen should be cleaned regularly to remove dirty ink residue, which spoils the recording by diminishing the capillary ink transport to the pen tip.

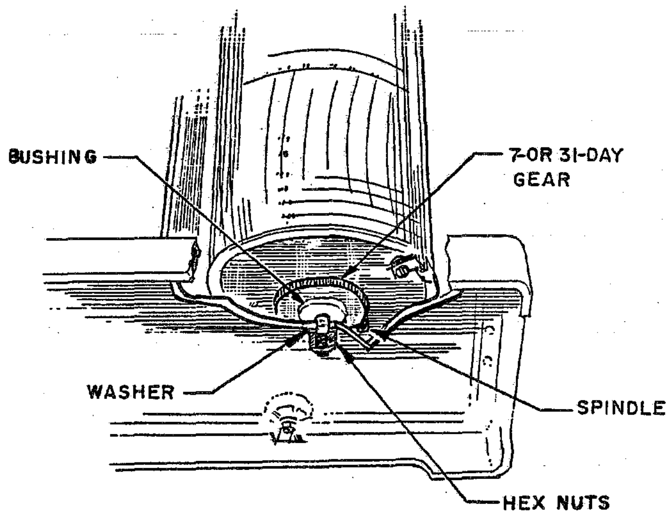


Figure 19 - Drum-unit assembly

The time co-ordinate of the recording is obtained through the rotation of the drum, around which the chart is wound. The drum rotation is effected by a clock, whose spindle protruding out of the base of the drum (Figure 19) is engaged with a cog-wheel fixed to the frame of the instrument. Spindle and cog-wheel are usually exchangeable in pairs, thus permitting a daily, weekly (or monthly*) drive of the drum to be obtained. The recording chart, wound around the drum in such a way that its lower edge "sits" tightly on the flange of the drum, is fastened to it by a clip. This spring clip holds together the overlapping ends of the chart. Before putting the drum back in place, the clock spring should be wound. The synchronization of the recording with an accurate clock is done with the recording pen set in position for recording. By turning the drum by hand in a direction to eliminate backlash, the proper time-scale division of the chart is brought under the pen tip.

The drum clock has a provision for adjustment of the retard/advance control lever (Figure 20). The speed of the clock should be adjusted carefully by an experienced operator with the help of a pair of pointed tweezers.

There are other recording systems in use. For the purposes of a monthly recording with the time detail of a weekly or even daily recording, a strip-chart recording mechanism may be used, either spring or electric-motor driven.

A time-marking arrangement should allow time marks to be made without lifting the cover of the instrument.

---

* Provided the clock's driving mechanism is designed for monthly drive!

Good barographs have efficient temperature compensation, enabling the temperature error for a 20°C change of temperature to be kept within the limits of 1 hPa. Scale error should not exceed 1.5 hPa at any point.

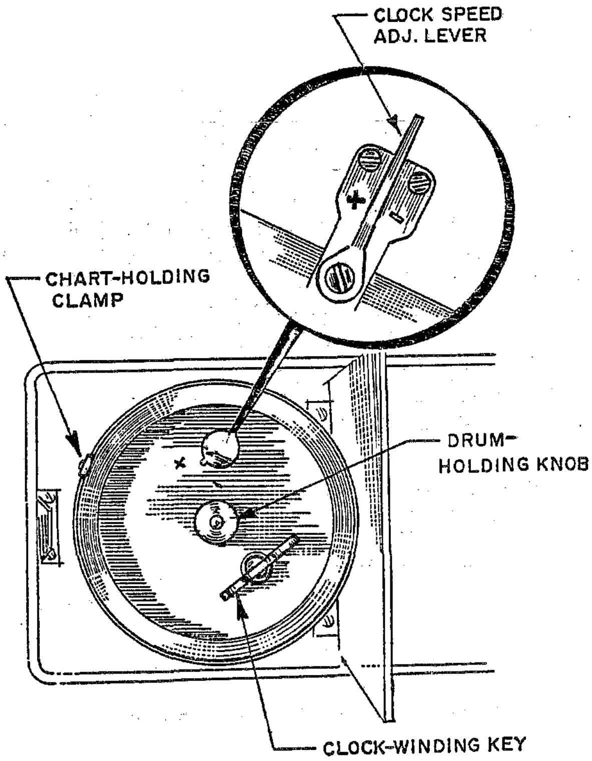


Figure 20 - Top view of drum unit

Hysteresis should be sufficiently small: a step-change of pressure amounting to 50 hPa and a return to the original value should not cause a hysteresis error exceeding 1 hPa.

When absolute pressure values are required from the barograph, the record should be compared with the corrected readings of the mercury barometer at least once every 24 hours.

The main source of error in the barograph, in addition to the errors stemming from the aneroid capsule, is the friction between the pen and the chart.

2.2.3 Hypsometers - measurement of pressure through boiling temperature

The boiling temperature of a liquid depends on the liquid itself and the atmospheric pressure. For a selected liquid, the boiling temperature is a function of the pressure. It is well known that pure water boils at 100°C at sea-level at an atmospheric pressure of 760 mm Hg. When the pressure decreases, the boiling temperature decreases. The design of a thermometric pressure-measuring instrument known as a hypsometer, is based on this property.

The ordinary hypsometer consists of an alcohol burner heating a boiling kettle containing purified water, its temperature being measured by a highly sensitive thermometer. Thermometers with a 0.02°C scale division are used, the temperature being read to 0.01°C. A semi-empirical formula may be used for the pressure evaluation, giving satisfactory results down to 500 hPa.

$$P = 760 + \frac{t_w - 100}{0.0375} \text{ mm}$$

An analytically-deduced expression, based on the Clausius-Clapeyron equation is used for upper-air measurements:

$$\log P = A - B/T$$

where:

A, B are constants depending on the hypsometric liquid used;

T is the boiling temperature of the liquid in kelvins.

A number of hypsometric liquids are used for upper-air pressure measurements, e.g. Freon-13, with a boiling point of -82°C/760 mm, carbon disulphide (CS_2), with a boiling point of + 46°C at 760 mm, etc.

A contemporary radiosonde thermos-flask thermistor hypsometer is shown in Figure 21. It is electrically heated (H) and the boiling point of the liquid used is measured by a thermistor sensor (T).

The hypsometer's accuracy improves with the decrease of the pressure measured. This is one reason why the instrument is most often applied as an upper-air pressure-measuring device.

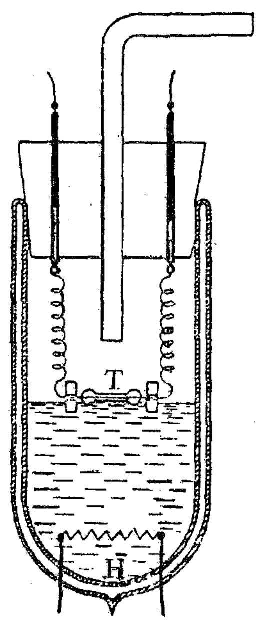


Figure 21 - Thermistor hypsometer

2.2.4 Altimeters - altitude-through-pressure measurements

As could logically be expected, knowing the nature of the atmospheric pressure, and the fact that it decreases with increasing height above ground, the ordinary aneroid barometer can be used for height measurements. The barometric formula, given below, can be used for the purpose:

$$H_2 - H_1 = 18\ 402.2(\log P_1/P_2)(1 + \alpha t_m)(1 + \beta e_m/P_m)(1 + 0.0026 \cos 2\varphi)(1 + \delta z_m)$$

where:

- H_1 = height above sea-level of reference point (m) (lower);
- H_2 = height above sea-level (unknown) of the point of interest (m);
- P_1, P_2 = pressure values respectively at H_1 and H_2;
- α = 0.00366, coefficient of thermal expansion of the air;
- t_m = $(t_1 + t_2)/2$, mean temperature of the layer between H_1 and H_2;
- β = 0.378, coefficient;
- e_m = mean water-vapour pressure in the layer between H_1 and H_2: $\frac{e_1 + e_2}{2}$;
- P_m = $(P_1 + P_2)/2$, mean atmospheric pressure of the layer of interest;
- φ = geographical latitude of the site of the measurement;
- δ = 0.196×10^{-6}, coefficient accounting for the change of the force of gravity with height above the Earth's surface;
- z_m = mean height.

For most practical purposes, the humidity, latitude and gravity corrections may be ignored and a simplified formula used:

$$\Delta h = H_2 - H_1 = 18\,402.2(\log P_1/P_2)(1 + 0.00366\ t_m).$$

The height-difference measurement with the use of the above formula is the more accurate, the shorter the time interval between the P_1 and P_2 pressure measurements (possibly simultaneous).

An instrument having a design similar to that of the aneroid barometer, but having a scale graduated in altitude units (metres), is known as an altimeter. The altimeter is provided with a second scale, visible through a window in the first one and controlled by a knob. The value of the atmospheric pressure on the site is set on the second scale, as a zero adjustment for the altitude scale. The calculation of the altimeter scale is based on an International Civil Aviation Organization (ICAO) recommended formula.

2.3 Exposure of atmospheric-pressure measuring instruments

Mercury barometers are instruments for indoor installation. The main requirements with regard to siting are a uniform and relatively stable temperature, away from draughts and direct sunshine, a stable and vertical mounting, adequate lighting conditions and protection against vibration and rough handling.

The best mercury barometer site would be a windowless, unheated basement room with an inside stable wall. A small electric fan may be used to prevent an undesirable temperature stratification building up inside the room.

A glass-windowed barometer cabinet fastened firmly to the wall would be good protection against occasional rough handling. The cabinet should be furnished with a hinged door, opening away from the barometer.

Inside the cabinet, the mercury barometer should be fastened to the wall, in a way ensuring its vertical position. It would be better to install the barometer using a vertical-axis pivoting link or gimbals. Readings made successively by turning the instrument about 180° would demonstrate whether it is vertical or not.

A light background behind the barometer's scale (for Fortin barometers, also behind the cistern) would contribute to the ease of reading it. An illuminator, preferably using white luminescent light, placed in a way to give good lighting to the scale and thermometer, would be an advantage. It should be remembered, where electric incandescent lamps are used, that their place of installation should not reduce the homogeneity of temperature around the instrument.

If gusty winds are frequent and are affecting the barometer's readings, a flexible plastic hose could be connected to the cistern inlet hole, the other end of the hose being brought outside the building, away from the dynamic pressure fluctuations and connected to a special "head", ensuring true static pressure.

As far as the exposure of the aneroid barometer is concerned, the requirements for the exposure of the mercury barometer also apply. In addition, the aneroid barometer should be read in the same position in which it has been calibrated. A slight tap with the finger before taking the reading is necessary, in order to help the pressure capsule overcome the friction in the mechanical linkages and bring the pointer to the correct position. The reading should be taken, as far as possible, to the nearest 0.1 hPa.

The same requirements apply to the exposure of the station barograph. It is advisable that the barograph be mounted on a sponge-rubber cushion - a satisfactory anti-vibration precaution.

Pressure-measurement instruments should be transported with great care.

Mercury barometers are transported in an upside-down position (cistern above the tube), securely fastened inside a special, spring-cushioned, portable wooden box. Barometers having a special "transport" bottom screw, should have it fitted in place of the operational screw, after the air-inlet screw has been tightened and the barometer brought carefully into the right position to enable the screws to be exchanged.

Jerky movements and excessive acceleration should be avoided at all times during transportation of mercury barometers.

Although not as susceptible to shock as mercury instruments, aneroid barometers should also be transported with care and always placed on their cushioned portable boxes.

Barographs are transported with their recording pen disengaged from the drum and usually in a box made of expanded polystyrene foam.

Atmospheric pressure changes during transportation should not drastically exceed the measuring range of the instrument, otherwise damage may result.

2.4 Testing and calibration of atmospheric-pressure measuring instruments

A detailed discussion of calibration facilities and methods is given in Part II of the present compendium of lecture notes.

A comparison of the station mercury barometer with a reference standard, by means of a travelling standard, should be undertaken at least once a year. Remedial action, consisting of repeating a comparison and repairing or replacing the barometer, is generally required when:

- The absolute error exceeds $\pm$ 0.25 mm or $\pm$ 0.3 hPa;

- The change of error exceeds ± 0.08 mm or ± 0.1 hPa;
- The error undergoes sudden shifts or exhibits erratic behaviour;
- The instrument shows mechanical defects.

A comparison is also made after any relocation of the station barometer.

As regards the aneroid barometer, comparison with the station barometer is carried out on a weekly basis. A comparison of the aneroid barometer with a standard barometer and a calibration is necessary after any repairs to the barometer.

A repair would be necessary when:

- A systematic and increasing error is detected;
- Erratic behaviour of the instrument is observed;
- Mechanical defects are observed.

The station barograph is compared with the station mercury barometer at least once every 24 hours, if absolute values of the pressure recording are required. Comparison may be carried out on a weekly basis if only the barometric tendency is required.

A comparison of the barograph with the standard barometer and full calibration would be necessary after a repair to the instrument. Grounds for repair are the same as for the aneroid barometer. In addition, the clock of the barograph is subject to maintenance and repair procedures.

A deviation in the timing of the barograph records from the official time by more than 10 minutes a week, attributable to the clock, would necessitate a rate adjustment of the clock.

Cleaning and oiling of the clock is not the subject of a special regulation, but if a replacement clock and drum are available, these maintenance procedures should be carried out every two years.

The repaired clock should be adjusted for rate before being issued to a meteorological station.

CHAPTER 3

MEASUREMENT OF AIR TEMPERATURE

3.1 Nature and units of measurement of air temperature - temperature scales used in meteorology - conversion

Temperature may be defined as a parameter of the thermal state of matter. The value of this parameter depends on the average kinetic energy of molecules. The measurement of temperature is possible because of the heat transfer between bodies at different levels of average molecular kinetic energy.

The temperatures of two objects in thermal contact will become equal as their respective levels of average molecular kinetic energies become equal owing to the transfer of energy between them.

The earliest known use of a relative temperature-measuring instrument, an air-thermometer (gas-thermometer), is attributed to Galileo c. 1584. The design of the mercury thermometer and its use for meteorological purposes is attributed to Fahrenheit c. 1721. As a zero of the scale of this thermometer, Fahrenheit used the lowest temperature he recorded in Danzig. For the upper fixed point on his scale he adopted the human body temperature of 96°F. This scale gave 32° as the freezing point of water and 212° as the boiling point.

Celsius invented the Centigrade scale but in an inverted form: its zero at the boiling point of water and 100° at the freezing point. Linnaeus reversed the Centigrade scale and established it in its present form. Its S.I. name is Celsius Scale.

For operational meteorological purposes, temperature is referred to the Celsius scale, based on 100 scale divisions between the points t_{ice} and t_s. The unit is called "degree Celsius", which is synonymous to "degree Centigrade" (now discontinued).

Temperature is an important parameter with regards to meteorology. Meteorologists are interested in air temperature, soil temperature and water temperature.

Temperature calibration is based on reproducible fixed points. Over the range of meteorological interest the points used are given in the table on page 36.

The S.I. unit of thermodynamic temperature is the kelvin (K). It is 1/273.16 of the temperature of the triple point of water above absolute zero.

$$t^{\circ}C = T\ K - 273.16$$

$$t^{\circ}C = 5/9\ (t_F - 32) \quad t^{\circ}C = 5\ (t^{\circ}F - 32)/9$$

$$t^{\circ}F = 9t^{\circ}C/5 + 32$$

Surface-air temperature is the temperature of the free air measured 1.25 - 2 m above the ground. For agricultural purposes, air temperature at various other different levels may be of interest. Measurements of air temperature should be taken at fixed times. The extremes of air temperature, minimum and maximum attained throughout the day, should be measured as well.

Defined fixed points of the International Practical Temperature Scale

Equilibrium state	Assigned value of IPT K	Assigned value of IPT °C
Equilibrium between the liquid and vapour phases of oxygen (boiling point of oxygen) at standard atmospheric pressure (1013.25 hPa)	90.188	-182.962
Equilibrium between the solid, liquid and vapour phases of water (triple point of water)	273.16	0.01
Equilibrium between the liquid and vapour phases of water (boiling point of water) at standard atmospheric pressure p_o. The temperature t as a function of the vapour pressure of water is given by the equation: $t = [100 + 2.7655 \times 10^{-2} (p - p_o) - 1.13393 \times 10^{-5} (p - p_o)^2 + 6.82509 \times 10^{-9} (p - p_o)^3]$ °C where p is the atmospheric pressure in hPa.	373.15	100

Secondary reference points and their temperatures on the International Practical Temperature Scale

Equilibrium state	IPT K	IPT °C
Equilibrium between the solid and vapour phases of carbon dioxide (sublimation point of carbon dioxide) at standard atmospheric pressure p_o (1013.25 hPa). The temperature t as a function of the vapour pressure of carbon dioxide is given by the equation: $t = [1.21036 \times 10^{-2} (p - p_o) - 8.91226 \times 10^{-6} (p - p_o)^2 - 78.476]$ °C where p is the atmospheric pressure in hPa.	194.674	-78.476
Equilibrium between the solid and liquid phases of mercury (freezing point of mercury) at standard atmospheric pressure	234.288	-38.862
Equilibrium between ice and air-saturated water (ice point) at standard atmospheric pressure	273.15	0.0
Equilibrium between the solid, liquid and vapour phases of phenoxybenzene (diphenyl ether) (triple point of phenoxybenzene)	300.02	26.87

Soil temperature is measured at standard depths: 5, 10, 20, 50 and 100 cm below the surface. Additional depths may be included.

A soil-temperature measurement site should be either bare soil or grass-covered. The site, if the surface is not representative of the surrounding area, should be not less than 100 m^2 in extent.

At agrometeorological observing stations, continuous records of air temperature and soil temperature at different levels are desirable.

3.2 Principles underlying the operation of air-temperature measuring instruments

The thermometer is an instrument for measuring temperature. Thermometers based on various principles are in current use in meteorology. The following five groups of thermometric devices (indicating or recording) will be discussed here:

(a) Liquid-in-glass thermometers (mercury-in-glass and spirit-in-glass);

(b) Liquid-in-metal thermometers;

(c) Bimetallic thermometers;

(d) Electrical resistance thermometers (thermistor and metal resistance);

(e) Thermocouples.

The above-listed groups of thermometers are used in direct temperature measurements, the sensor being at the point of measurement. Indirect temperature measurement, based on the principle of infra-red radiometry, is capable of measuring at a distance an average areal temperature. As their application is still limited to special research purposes, they are not discussed in this compendium.

3.2.1 Mercury-in-glass thermometers

For routine measurement of temperature the use of the mercury-in-glass thermometer is almost universal. Its design is familiar to all: a glass capillary tube with a bulbous widening at one end (the mercury reservoir or bulb) and sealed at the other, is graduated in degrees after calibration. The space above the mercury meniscus in the capillary is evacuated.

As the temperature of the instrument changes, the mercury in the bulb changes in volume to a far greater extent than the glass, causing a change in the length of the mercury column in the capillary, proportional to the change in temperature. The following relationship is valid in this case:

$$\Delta V = A.\Delta l \quad ...... \qquad (1)$$

where:

ΔV = change of volume of the mercury in the reservoir, due to the change of temperature;

A = cross-sectional area of the capillary tube;

Δl = change of the mercury column length due to the change of volume ΔV.

Equation (1) simply states that the change in volume of the reservoir mercury is equal to the change in volume of the column mercury, assuming the capillary is unaffected by the temperature change.

However, changes in the dimensions of the glass bulb due to temperature changes are significant and the following relationship takes this into account:

$$\Delta V = V_o(g_1 - g_2).\Delta t \qquad (2)$$

where:

Δt = temperature change;

V_o = volume of the mercury inside the bulb at a "standard" temperature;

g_1 = cubic coefficient of thermal expansion of mercury = 0.000181;

g_2 = cubic coefficient of thermal expansion of the thermometric glass = 0.0000253 (for a chemical composition of the glass: SiO_2 - 67.5 per cent, Al_2O_3 - 2.5 per cent, B_2O_3 - 2.0 per cent, CaO - 7.0 per cent, ZnO - 7.0 per cent, Na_2O - 14.0 per cent).

Combining (1) and (2) gives:

$$\Delta 1 = \frac{V_o(g_1 - g_2)}{A}.\Delta t \qquad (3)$$

Equation (3) is an expression of the sensitivity of the thermometer: the larger the reservoir and the smaller the cross-section of the capillary, the higher the sensitivity. A large reservoir, however, means a longer settling time for the thermometer.

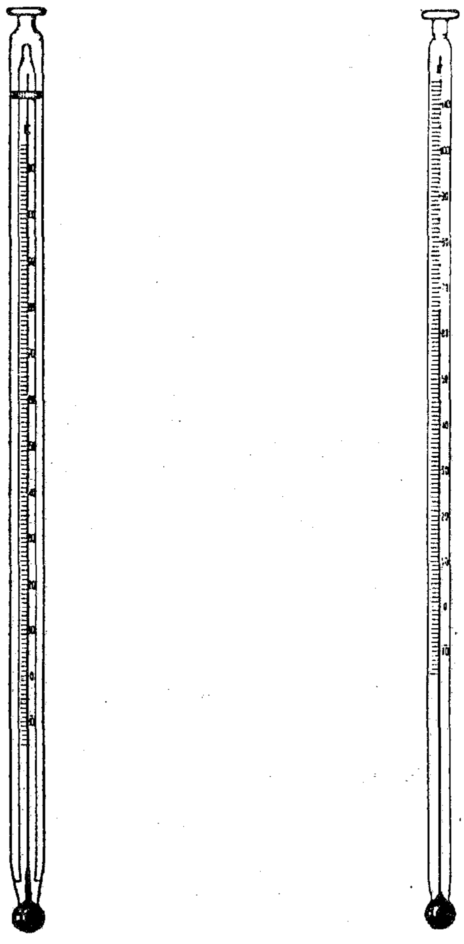


Figure 22 - Ordinary sheathed and solid-stem thermometers

Mercury has considerable advantages as a thermometric liquid: small thermal capacity, high thermal conductivity, no wetting of the capillary and a high boiling point. Its only disadvantage is its relatively high freezing point of -38°C. The addition of thallium to the mercury lowers its freezing temperature to -58°C.

A number of types of mercury-in-glass thermometers are used in meteorology:

(a) Sheathed station mercury thermometer, 390 - 430 mm long; outer body diameter 15 - 17 mm; scale division 0.2°C; temperature range -30 - 60°C (Figure 22);

(b) Maximum station thermometer, sheathed type, is similar in outward appearance to the ordinary station thermometer, apart from the constriction near the bulb, the temperature range and the scale division (0.5°C). The constriction of the maximum thermometer (Figure 23) allows the passage of mercury from the reservoir to the capillary, but prevents the return passage of the mercury by itself. As the mercury column is unable to return, it will remain at the highest point reached since last being reset.

In order to prepare the maximum thermometer for the following day, it needs to be re-set, which is done by gently swinging the thermometer, bulb down, so as to force the excess mercury down into the bulb;

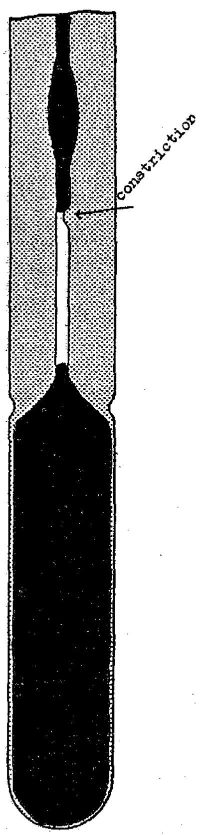


Figure 23 - Bulb of maximum thermometer

(c) The aspirated psychrometer's mercury thermometer is of the sheathed type, but shorter (265 - 275 mm) and more slender (diameter = 7 - 8 mm) than the ordinary station thermometer. Its scale division is 0.2°C. The thermometer has a metal cap with a flange enabling secure fastening of the instrument to the metal body of the psychrometer;

(d) Soil thermometer. This is usually a mercury thermometer with a long stem bent at right angles. The reservoir and part of the stem are buried in the ground, the scale facing up and lying on the ground, so that the reading can be taken without the thermometer being removed.

Some soil thermometers are inclined at 45° and are installed propped on a wooden support.

For greater depths, a straight soil thermometer is used, placed in a plastic container, heavily lagged by embedding its reservoir in wax. These kinds of soil thermometer are placed in tubes of larger diameter sunk to the necessary depth in the ground. To read the thermometer, it is taken out of its tube. The great lag-coefficient prevents the thermometer from changing its reading while it is being read;

(e) Mercury-in-steel thermometers are based on the same principle of thermal expansion of the thermometric liquid as the mercury-in-glass ones. They are usually designed for remote reading of the temperature (up to 50 m). The reservoir is a steel one and a thin steel capillary, protected by a lead cover, connects the reservoir to the indicating device. The indicator is a Bourdon tube, with a cog-wheel segment/pinion amplifier, driving the pointer or the recording pen-arm. In order to neutralize the effect of temperature changes on the capillary tube, a conpensating device is necessary, positioned in a connecting link in the capillary. The compensating device consists of an inert steel wire inside the connecting link, having a suitable thermal expansion, so that the expansion of the capillary, with rising temperature, is compensated by a corresponding expansion of the wire.

3.2.2 Spirit-in-glass thermometers

Thermometers designed for use below the freezing temperature of mercury use different thermometric liquids with lower melting points (toluol, alcohol).

(a) The spirit-in-glass minimum thermometer has a construction permitting the minimum temperature indication to be retained until the thermometer is reset. Looking like the ordinary station thermometer, externally, the minimum thermometer has a larger reservoir of a special design and an increased surface area. This is necessary, because spirit (as well as toluol) has a lower thermal conductivity and a larger heat capacity. The capillary is of a somewhat larger bore and inside the spirit column there is a movable, glass index (Figure 24).

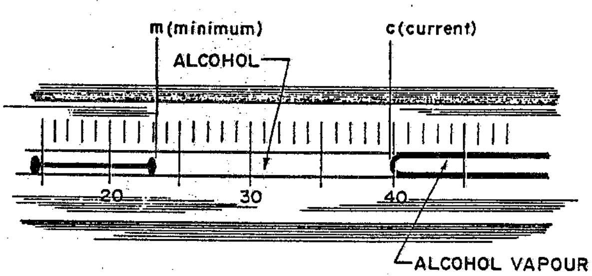


Figure 24 - Segment of spirit minimum thermometer

As the temperature falls, the meniscus of the spirit column pushes the glass index along the tube. As the temperature rises, the spirit flows past the index, leaving the indication at the lowest temperature reached.

To prevent the index from moving under gravity, the thermometer is used in an almost-horizontal position with the bulb end slightly lower. The index is light-weight, with rounded ends, unable to pierce the surface tension "membrane" of the spirit meniscus.

To reset the minimum thermometer, it is necessary to incline it slightly, reservoir up, until the glass index slides and stops at the spirit-column meniscus.

Spirit minimum thermometers should withstand temperatures as high as 65°C. For this purpose, a safety expansion chamber is provided at the upper end of the capillary. There are ordinary station thermometers of the spirit-in-glass type, for use in very low temperatures.

The spirit of the thermometer should have a good, fast colouring. With thermometers using ethyl alcohol, the alcohol should be of a high purity and free from acetone, in order to preserve adequate calibration characteristics;

(b) The maximum-minimum thermometer is, in essence, a spirit thermometer. It has a U-shaped capillary with a bulb at each end, serving as a reservoir. The U-shaped capillary is partly filled with mercury, above which in the left-hand leg there is spirit, which also fills the reservoir. The space above the mercury column in the right-hand leg is also filled with spirit, but the reservoir is only part full of spirit, the remaining space containing air and spirit vapour.

Two spring-loaded light-weight steel indices, one in each leg, are moved by the mercury column menisci as they move. With the temperature increasing, the spirit in the left-hand side reservoir expands, pushing the mercury column further into the right leg of the capillary and moving the corresponding index upward. The spirit in the right-hand leg is forced into the reservoir compressing the air and vapour there. The right-hand side index is pushed as far up as the scale division indicating the maximum temperature. With the temperature decreasing, the spirit in the left leg contracts, the mercury column is forced into the left-hand leg by the pressure of the spirit vapour and air in the right-hand reservoir, moving the left-hand index to the minumum temperature position. Thus the instrument can indicate both extremes of temperature.

Re-setting is achieved with the help of a magnet. This is used to bring the minimum temperature index and the maximum temperature index down to their respective meniscus of the mercury in the capillary.

The quality of a liquid-in-glass thermometer depends very much on craftmanship and the thermometric liquid used. Accuracy depends on the uniformity of the capillary's bore. Some features of the most widely used thermometric liquids are given on page 42.

The ideal thermometric liquid should have the lowest melting point possible, the highest boiling point possible, an appreciable coefficient of thermal expansion, a low thermal capacity and a high heat conductivity, with no wetting properties. It should not change either physically or chemically because of radiation or other factors.

The set of station thermometers is used with a special thermometer mount, installed in the Stevenson screen (Figure 25).

Features of thermometric liquids

Thermometric liquid	Melting point °C	Boiling point °C	Coefficient of thermal expansion	Heat capacity J/K	Thermal conductivity W m^{-1} K^{-1}	Wetting yes/no
Mercury	-38.9	336.9	0.000181	0.12	8.3610	no
Alcohol	-117.3	78.5	0.00110	2.43	0.1800	yes
Toluol	-95.1	110.5	0.00109	1.51	0.1591	yes

The mount, made from wood, cast aluminium or brass, ensures an almost-horizontal position for the minimum and maximum thermometers (reservoirs slightly lower than heads of the thermometers) and has provision for holding the dry and wet thermometers, together with a distilled water container for the psychrometer.

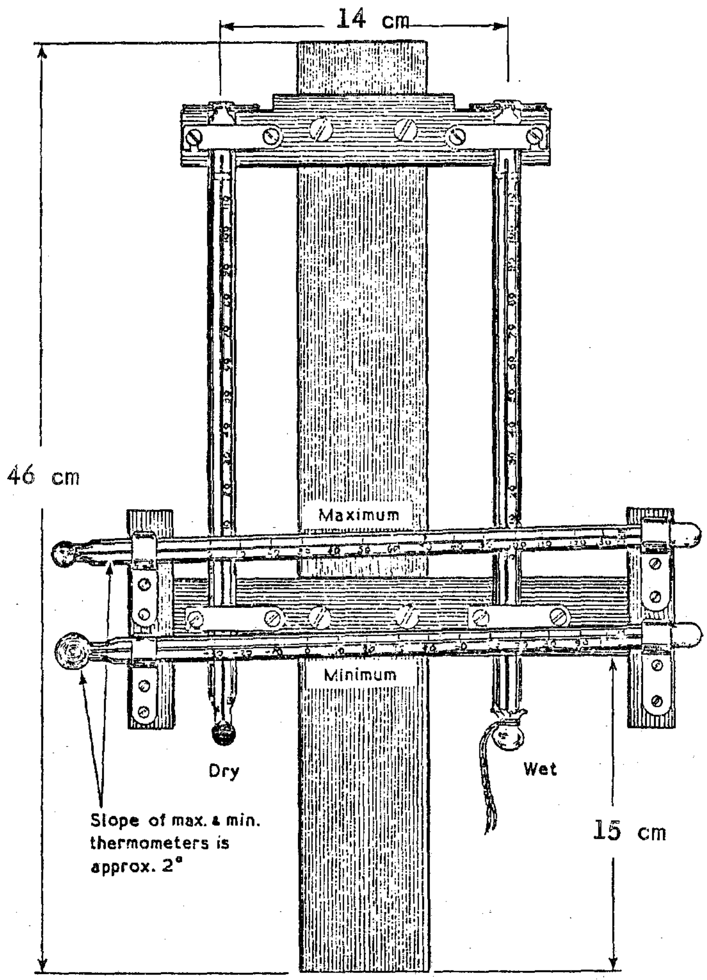


Figure 25 - Thermometers mounted in a shelter

Thermometer-accuracy requirements

Thermometer type	Ordinary	Maximum	Minimum
Span of scale (°C)	-39 to +45	-30 to +50	-40 to +40
Range of calibration (°C)	-30 to +40	-25 to +40	-30 to +30
Maximum error	<0.2 K	±0.2 K	±0.3 K
Maximum difference between maximum and minimum correction within the range	0.2 K	0.3 K	0.5 K
Maximum variation of correction within any interval of 10°C	0.1 K	0.1 K	0.2 K

The following sources of error should be considered with measurements with the liquid-in-glass thermometers:

(a) Elastic errors

(i) Reversible and, depending on the thermometric glass used, 0.05° (high-quality glass) up to 1.0°C (low-quality glass) for a variation of the measurement temperature over a 100° interval;

(ii) Irreversible (secular), caused by the shrinking of the thermometer's bulb with time - about 0.01°C during the first year, less afterwards;

(b) Capillary errors, due to irregularity in the bore of the capillary along its length;

(c) Scale-division errors;

(d) Errors due to the irregularity of expansion of mercury and glass over the whole range of measurable temperatures.

Errors may be introduced during the calibration of the thermometer, if only the reservoir is immersed in the calibration liquid. Total immersion calibration of thermometers is the right procedure, because in real conditions, the whole of the thermometer is exposed to the changes of temperature.

The parallax error has not been mentioned but the observer should be aware that if the observer's eye is not level with the meniscus of the mercury column, an error in the reading may result.

Radiation from the observer's body may cause a quite substantial error if the observer, due to impaired vision or habit, comes too close to the thermometers while reading them.

3.2.3 The bimetallic thermometer - station thermograph

Two thin metal strips, having different coefficients of thermal expansion of their respective metals, roll-welded together along one of their flat sides, form a bimetallic strip. If such a strip is clamped at one end with the other end free to move, a change in temperature makes the bimetallic strip bend towards the side of the metal which has the smaller value of thermal expansion coefficient (provided the change is an increase of temperature over the initial one). The displacement of the free end of the bimetallic temperature sensor is proportional to the temperature change (Figure 26).

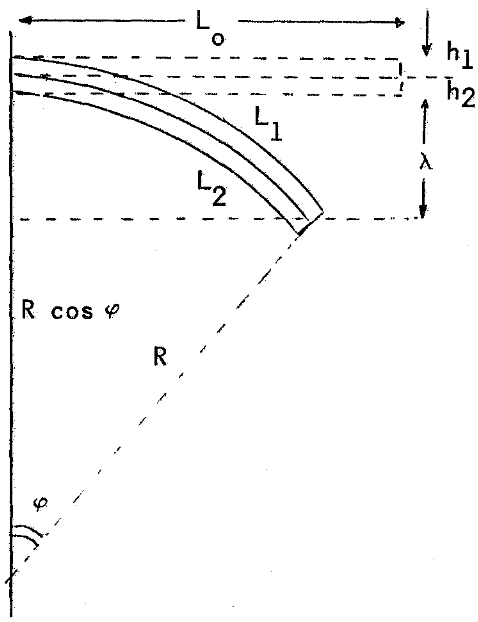


Figure 26 - Temperature effect on a bimetallic strip

In order to find an analytical expression for the displacement λ of the bimetallic strip's free end, as a function of the temperature t, consider a strip of two metal components of thicknesses h_1, h_2, having coefficients of thermal expansion, a_1, a_2, respectively.

Assume that the bimetallic strip is straight with length L_o at 0°C. Further, assume that at temperature t, the bimetallic strip is bent downwards (as illustrated), having a displacement of the free end λ. An additional assumption is made that the strip bends along a circle of radius R.

With the assumptions made and according to Figure 26, the radius of the upper strip will be $R+h_1$, while that of the lower strip $R-h_2$. The following relationship will be valid:

$$L_1 = (R + h_1)\varphi \qquad (1a)$$

$$L_2 = (R - h_2)\varphi \qquad (1b)$$

where L_1 and L_2 are the respective lengths of the upper and lower strips at the temperature t. The entity φ is the central angle of the circular bimetallic segment.

Subtracting equations (1a) and (1b) from each other gives:

$$\varphi = \frac{L_1 - L_2}{h_1 + h_2} \qquad (2)$$

The change of length of each bimetallic component follows the law:

$$L_t = L_o\ (1 + at),$$

which applied to the present case gives:

$$L_1 = L_o\ (1 + a_1 t)$$
$$L_2 = L_o\ (1 + a_2 t) \qquad (3)$$

L_o is the length of the bimetallic strip at 0°C and a_1, a_2 are the respective thermal coefficients of expansion of the components.

Substituting L_1 and L_2 from (3) into equation (2) yields:

$$\varphi = \frac{L_o\ (a_1 - a_2)t}{h_1 + h_2} \qquad (4)$$

An expression for the displacement of the free end of the strip due to the temperature change can be expressed in terms of R and :

$$\lambda = R - R \cos\varphi \qquad (5)$$

Keeping in mind the trigonometric relationship

$$1 - \cos\varphi = 2\sin^2\frac{\varphi}{2}$$

and knowing that φ is relatively small, so that we could justifiably write: $\sin^2\varphi/2 = (\varphi/2)^2$ and substituting R by L_o/φ we can re-write equation (5) as follows:

$$\lambda = 2\ R\ \sin^2\varphi/2 = 2\ (L_o/\varphi)(\varphi/2)^2 \qquad (6)$$

Finally, substituting for φ from (4) we have:

$$\lambda = \frac{L_o^2 . a . t}{2 . h} \qquad (7)$$

where:

$$a = (a_1 - a_2) \text{ and } h = (h_1 + h_2)$$

Since L_o, a and h are constants, we are justified in writing:

$$\lambda = A . t \qquad (8)$$

where:

$$A = a . L_o^2/2h$$

Thus the displacement of the free end of the bimetallic strip with the change of temperature is seen to be a linear function of the temperature.

A more detailed analysis of the response of the bimetallic sensor to temperature changes involves the Young's modulus, E, of the metal strips. The following relationship is readily obtained:

$$h_1/h_2 = \sqrt{E_2/E_1}$$

where E_1 and E_2 are the respective values of Young's modulus for the two metal strips of the sensor.

From the above analysis it can be inferred that the sensitivity of the bimetallic sensor is directly proportional to the square of the length of the strip and to the difference in the thermal coefficients of expansion and is indirectly proportional to the thickness of the bimetallic strip.

Bimetallic temperature sensors have a number of meteorological applications, an important one being station thermographs.

The station thermograph is a temperature-recording instrument. The thermograph has a similar recording system to that of the barograph, consisting of a daily or weekly clock-driven drum, paper, thermograph chart and an ink recording pen, controlled by a mechanical signal converter, actuated by the signal of the temperature sensor, a Bourdon thermosensitive tube, or more often a bimetallic sensor. The bimetallic semicircle or helix has certain advantages over other mechanical sensors, which is why the bimetallic thermograph is under discussion here (Figure 27).

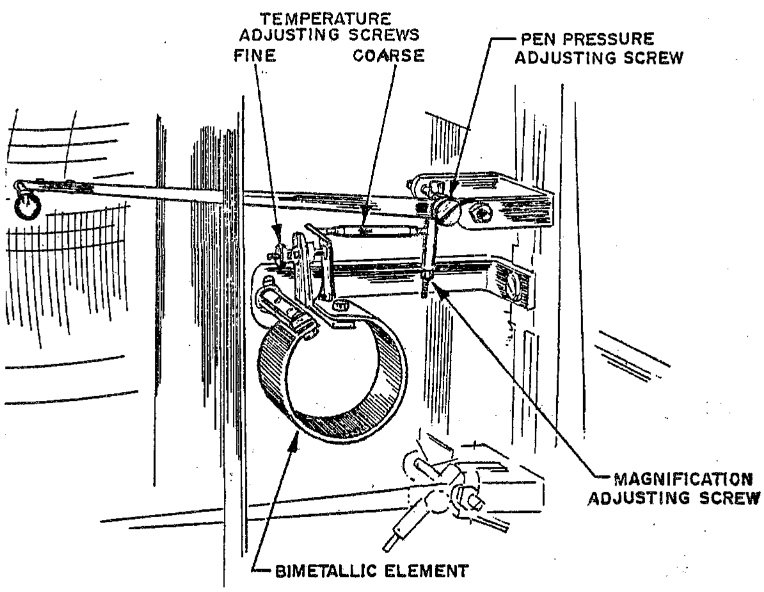


Figure 27 - Recording assembly of a thermograph

The conventional thermograph usually has a base-plate of cast duralumin, which supports the drum, recording system and sensor. A lid with a glass window permits easy reading of the record, whilst preventing possible damage or deterioration caused by the weather.

The lever-magnification system of the thermograph is provided with a means of adjusting the temperature scale (pure translation of the scale within a few degrees Celsius). Some thermograph systems have a magnification adjustment screw, permitting the change of the thermograph sensitivity and range (Figure 27). A change in the magnification of the instrument would mean the use of new recording charts, having a different scale. This operation, if necessary, can only be performed by highly skilled personnel using the facilities of a calibration laboratory.

The temperature range of different makes of thermograph may vary between 60° and 90°C, and scale divisions between 1.5 mm per degree and 1.0 mm per degree. The time scale is typically one scale division = 15 min for daily clocks and 2 h for weekly clocks.

The accuracy of the temperature records rarely exceeds one per cent.

The lag-coefficient with a ventilation rate of 1 m s^{-1} is more than 200 s. It changes also with the characteristics of the Stevenson screen.

A mechanism for stopping the recording, by lifting the pen off the paper, is actuated by a lever which is accessible without lifting the lid of the instrument, as is the time-marking device.

The records from the thermograph are checked daily against the station thermometer or, even better, against the minimum and maximum thermometers. Laboratory checks of the instrument are recommended at least once every two years. These checks should coincide with the routine maintenance (cleaning and oiling) of the clock-mechanism.

Sources of error are:

- Corrosion, dents or bends in the bimetallic strip;
- Friction in the mechanical lever system. Dirt or excessive friction due to the effects of weather on the metal seriously affect the accuracy of the instrument, much more than with other types of sensor because of the relatively small power of the bimetallic strip;
- Excessive friction between pen and chart. Instruments having a gate suspension are less liable to errors of this kind.

Because of its exposure in the meteorological screen, the instrument needs more frequent cleaning, especially in conditions of dust, sand or industrial pollution of the air. Regular cleaning of the recording pen with alcohol, in order to improve its capillary properties, is recommended at monthly intervals.

3.2.4 Electrical resistance thermometers

Two types of electrical resistance thermometers are used in meteorology: metal resistance, having a positive temperature coefficient of resistance and semi-conductor resistance thermometers, the majority of which have a negative temperature coefficient of resistance.

The use of metal resistance thermometers as temperature sensors is based on the following well-known relationship:

$$R_t = R_o \left(1 + a\,(t - t_o) + b\,(t - t_o)^2\right) \ldots. \qquad (1)$$

where:

R_t = resistance of the metal resistor at temperature t°C;

R_o = resistance of the metal resistor at a fixed temperature t_o;

a,b, are constants, depending on the metal used.

For resistive sensors used within the meteorological range of temperatures, the following abridged relationship can be used:

$$R_t = R_o \left(1 + a \left(t - t_o\right)\right) \tag{2}$$

The choice of the metal of the resistor, to be used as a temperature sensor is based on few considerations:

- The required sensitivity of the instrument;
- The compatibility of the physical properties of the metal with the purpose of its use;
- Economic considerations.

The following metals in the form of wire, are in common use as temperature sensors: platinum, nickel, copper and iron. While other metals might be used for some special applications, preference is given to platinum and copper, as far as meteorology is concerned.

An idea of the suitability of the different metals, as far as their temperature resistance coefficient is concerned, is given in the table below:

Metal	Fe	Cu	Ni	Pt	Ag	Constantan	Manganin
$a \times 10^4$	62	43	52	38	10.5	0.3	0.07

The figures presented in the table are valid within the temperature range 0° - 100°C. It is evident that iron and copper have relatively high values of temperature coefficient of resistance, but they both have much inferior characteristics as regards stability and corrosion compared to platinum.

Platinum wire, 0.1 mm in diameter or less, wound either on a ceramic or glass rod of about 4 mm diameter and 30 - 40 mm length, covered by a protective ceramic or glass layer and having a resistance at 0°C of 100 Ω is widely used as a temperature sensor. An additional protective sheath with a suitable waterproof cable connexion is often used with this kind of sensor.

Platinum wire sensors have excellent stability and an almost linear response over the meteorological temperature range.

A number of electrical circuits for signal conversion and indication are used with metal resistance sensors for temperature, three of which are described below.

<u>The Wheatstone bridge</u> comprises four resistors - r_1, r_2, r_3 and r_t - arranged as in Figure 28. A voltage, U, is applied across one pair of diagonally opposed points and a sensitive current-measuring instrument (a galvanometer) is connected across the other pair. If the values of the four resistors are such that $r_1/r_2 = r_3/r_t$, then the potential difference between the points of connexion of the galvanometer will be zero and no current will flow through the galvanometer.

If r_t represents a temperature-dependent resistance and r_2 is a variable resistor with some means of manual variation and read-out of its value, the system may be used to measure the change in resistance of r_t as its temperature changes. As r_t varies, the bridge will become unbalanced and current will flow through the galvanometer. The balance may be restored by means of the variable resistor and its new value read-off.

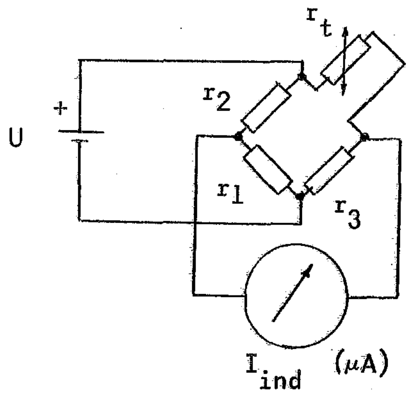


Figure 28 - Circuit diagram of a Wheatstone bridge

Properties of metals used in the construction of metal resistance thermometers

Metal	Melting point	Working temperature/maximum
Platinum (Pt)	1 773.5°C	540°C
Nickel (Ni)	1 455.0°	300°
Copper (Cu)	1 083.0°	120°

Functional relationship resistance/temperature for platinum:

Temperature interval of validity of relationship: $0°C \leqslant t < 750°C$

Relationship used: $R_t = R_o\ (1 + At + Bt^2)$

Numerical values of coefficients: $A = 3.96847 \times 10^{-3}\ °C^{-1}$

$B = -5.847 \times 10^{-7}\ °C^{-2}$

$C = -4.22 \times 10^{-12}\ °C^{-3}$

Temperature interval of validity of relationship: $0°C > t \geqslant -200°C$

Relationship used: $R_t = R_o\ (1 + At + Bt^2 + C/t - 100/t^3)$

Functional relationship resistance temperature for copper:

Temperature interval of validity of relationship: $-50°C \leqslant t \leqslant 120°C$

Relationship used: $R_t = R_o\ (1 + aT)$

Numerical value of coefficient: $a = 4{,}26 \times 10^{-3}\ °C^{-1}$

Calibration values - resistance/temperature

Platinum resistance thermometer					
0°C	20°C	40°C	60°C	80°C	°C
(Ω)					
17.28	-	-	-	-	-200°
59.65	51.38	43.01	34.56	25.98	-100°
100.00	92.04	84.03	75.96	67.84	-0°
100.00	107.91	115.78	123.60	131.37	+0°
139.10	146.78	154.41	162.00	169.54	+100°
177.03	184.48	198.88	199.23	206.53	+200°
Copper resistance thermometer					
0°C	20°C	40°C	60°C	80°C	°C
(Ω)					
78.70	-	-	-	-	-50°
100.00	91.48	82.96	-	-	-0°
100.00	108.52	117.04	125.56	134.08	+0°
142.60	151.12	159.64	168.16	-	+100°

From the bridge relationship presented above and with the values of r_1, r_2, r_3, known, the value of r_t can be found. Further, through equation (2) p.48, the actual temperature change can be found (in the case of t_o = 0°C, this will be the temperature measured): $r_t = r_3\ (r_2/r_1)$ and $(t - t_o) = {}^{\circ}(r_t - r_o)/r_o$.

A further step is to calibrate the dial of the variable resistor in degrees, thus reading the measured temperature directly.

The process could be "mechanized" through the use of an electronic potentiometer, a device capable of mechanically adjusting the variable resistor in such a way as to maintain the voltage difference between the points of connexion of the indicator zero and hence the current through the indicator will be zero.

The electronic potentiometer is described in more detail in the chapter on recording solar radiation.

The configuration of the circuit of <u>the out-of-balance bridge</u> is the same for the balanced bridge (Figure 28) except that r_2 is a fixed resistor and the sensitive galvanometer is replaced by a microammeter with a range of a few hundred microamperes.

Based on theoretical considerations (Part III) the following formula is applicable to the relationship between the value of r_t and the current through the indicator:

$$I_i = U \frac{(r_1 r_t - r_2 r_3)}{R(r_1+r_2)(r_3+r_4)+r_1 r_2(r_3+r_t)+r_3 r_t(r_1+r_2)}$$

where:

I_i = current through the indicator (microammeter);

R = internal resistance of the indicator.

The rest of the parameters in the expression for the bridge current (U, r_1, r_2, r_3, r_t) are as indicated in Figure 28.

It can be seen from the expression for I_i that the indicator current is not a linear function of the temperature. With a proper choice of bridge components, however, linearity can be improved within a relatively wide temperature range (30°C). Using three ranges, i.e. with a range switch in the r_2 branch of the bridge, switching in one of three different values r_2', r_2'' or r_2''' a 90° temperature interval can be covered while still retaining a satisfactory linearity. In order to compensate for the change of resistance with temperature along the cable by a remote measurement and eliminate the "cable-introduced error", a three-lead bridge circuit can be used (Figure 29).

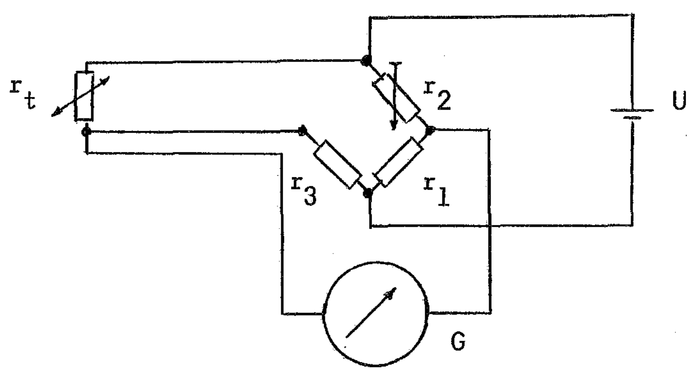


Figure 29 - Circuit diagram of a three-lead bridge

The unbalanced Wheatstone bridge can be used with a different moving coil instrument, one having two coils, active and reactive. This kind of moving coil indicator is known as a ratio-meter (Figure 30). Its principle will be briefly discussed in the following paragraphs.

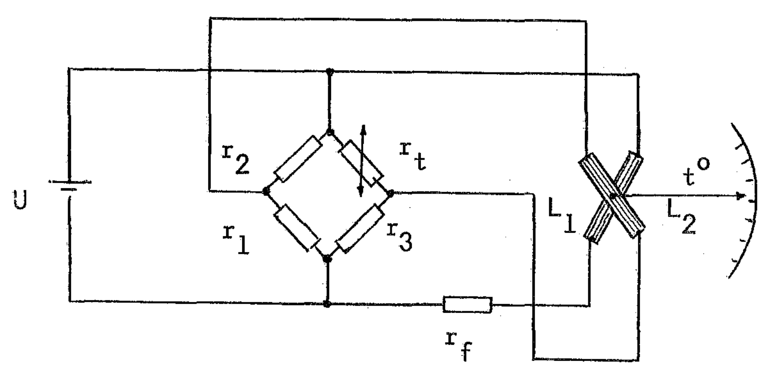


Figure 30 - Ratio-meter and bridge-circuit

A cut-away view of a moving coil instrument (milliammeter or microammeter) is shown in Figure 31. A horseshoe magnet with suitably-shaped pole pieces and an iron core of cylindrical shape, create a highly homogeneous magnetic field in the air gap between the pole pieces and the iron core. A wire-wound coil is free to rotate about a vertical axis, supported on a fine, clockwork bearing.

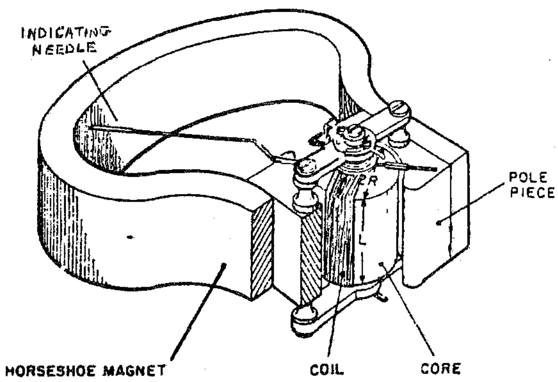


Figure 31 - Moving-coil indicator

The coil carries a light-weight pointer indicating the current on a scale. The coil winding is connected to the terminals of the instrument through two hairsprings, which keep the pointer on the zero position when no current passes through the winding.

When current passes through the coil, assuming correct polarity, the interaction between the magnetic field produced around the coil and that of the horseshoe magnet causes the soil to rotate on its bearings. The two hairsprings resist the rotation and the coil comes to rest at some equilibrium position, determined by the following relationships:

$$M_1 = k_1 . I . w . B \qquad (1)$$

$$M_2 = k_2 a \qquad (2)$$

where:

M_1 = torque produced as a result of interaction between current and magnetic field;

k_1 = coefficient of proportionality;

I = current through the coil winding;

w = number of turns in the winding;

B = magnetic induction in the air gap;

M_2 = the springs' counteracting elastic torque;

k_2 = coefficient of proportionality;

a = angle of the coil/pointer deflection.

With an equilibrium attained:

$$M_1 = M_2 \qquad (3)$$

therefore:

$$a = k.w.I.B \tag{4}$$

where:

$$k = k_1/k_2$$

and if k.w.B = A, another constant, we obtain:

$$a = A.I \tag{5}$$

Thus the deflection of the pointer of the moving coil instrument is seen to be proportional to the current passing through the coil windings.

The way the indicator's parameters: (spring torque, number of turns in the windings and value of the magnetic induction) affect the instrument's sensitivity is clear from equation (4).

As a circuit element, the moving coil instrument's internal resistance R should be considered as well;

Electrical resistance thermometers can be used with a different type of signal converter/indicator device known as a ratio-meter: the ratio-meter is basically a moving coil instrument for measurement of electrical current. It is basically similar to the milliammeter already described, but with pole pieces shaped differently from the horeshoe magnet.

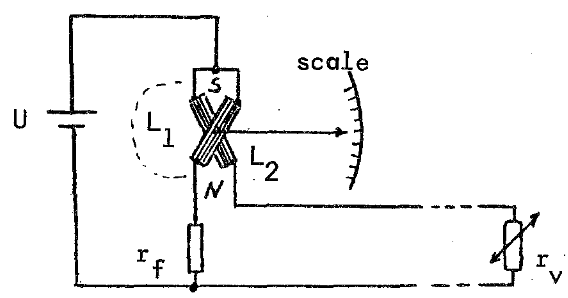


Figure 32 - Circuit of a ratio-meter

Instead of one moving coil, it has a "twin" moving coil, consisting of two symmetrical coils, at a small angle to each other, fastened firmly to a common axis. The coils are wound in such a way, that by passing through them currents of equal strenth, they oppose each other in their interaction with the magnetic field, so that no electrical torque is produced.

In the circuit shown in Figure 32, the fixed value resistor r_f passes a fixed current through one of the coils. The current through the other coil depends on the value of the varying resistance of r_v. The difference in these two currents will cause the twin coil to be deflected to an extent which is a measure of the ratio of the two currents. Without going into greater detail, it can be demonstrated that the deflection, a, will be a function of the ratio of measurement current, I_t, and the fixed current, I_f:

$$a = f(I_t/I_f)$$

The response of this type of indicator is reasonably linear, while having a good stability with a changing source voltage.

A three-lead system (Figure 33) is especially well-suited to remote reading, with the effect of a temperature gradient along the cable connecting the sensor being eliminated.

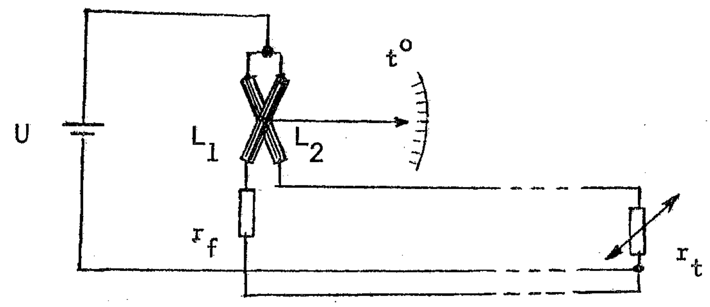


Figure 33 - Three-lead ratio-meter circuit

The ratio-meter is suited for heavy-duty, industrial use.

In general, the electrical resistance thermometer has a satisfactory calibration stability. The copper-wire sensor has a limited temperature interval, because of the liability of copper to oxidation by high temperatures while iron is even worse in this respect. Platinum, in spite of its high cost and relatively low thermal coefficient of resistance is the most widely-used material for resistive temperature sensors.

Sources of error of the metal resistance thermometer are:

(a) For platinum sensor, balanced-bridge configuration:

- (i) Increased resistance between the wire and slide contact in the variable resistor due to dirt or oxidation;
- (ii) Drift in the values of the resistors in the bridge;
- (iii) Decrease in sensitivity of the zero indicator.

(b) For platinum sensor, out-of-balance configuration:

- (i) Variations in the voltage of the electrical source;
- (ii) Drift in the value of the bridge components;
- (iii) Change in sensitivity of the indicator (e.g. after repair);
- (iv) Self heating because of a large current.

(c) For platinum sensor, ratio-meter:

- (i) Drift of the value of the fixed resistor;
- (ii) Temperature gradient along the sensor cable in a remote-reading, two-wire system.

One type of <u>semiconductor resistance thermometer</u> is the thermistor. Thermistors are temperature-sensitive resistors, based on semi-conductor material, many of them having a negative temperature coefficient. With an increase of temperature, the electrical resistance of many of them decreases, unlike metal resistance sensors.

The relationship between the electrical resistance of the thermistor and its temperature is an exponential one and can be expressed as follows:

$$R = A . e^{a/T} \tag{1}$$

where:

A and a are constants depending on the material used;

T is the temperature in kelvins of the thermistor.

The temperature coefficient of the thermistor could be obtained from (1) through differentiation:

$$b = \frac{1}{R}\frac{dR}{dT} = - a/T^2 \tag{2}$$

The value of b is approximately four per cent per degree.

In Figure 34, a plot of the thermistor R = f(T°) curve is given, together with curves of different metal resistors, over the same temperature interval: the thermistor has an approximately ten-fold higher sensitivity than metal resistors.

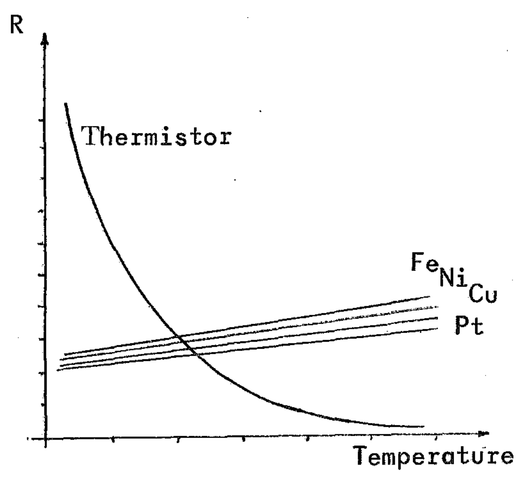


Figure 34 - Plot of resistance versus temperature - different materials

Logarithms can be taken on both sides of equation (1):

$$\ln R = \ln A + a/T \tag{3}$$

Using a semi-logarithmic co-ordinate system, equation (3) can conveniently be represented by a straight line and used for calibration purposes.

Experimental samples of thermistors can easily be made under laboratory conditions:

Mix powdered Mn_2 and NiO in a proportion of 1:1. Add an equal amount of PbO and stir again. Add CuO, either 100 mg per gram of mixture (kΩ range of thermistors), or 10 mg per gram of mixture (hundreds of kΩ range of thermistors, at 20°C). Add water and stir thoroughly until a viscous mixture is obtained. Take a crumb of the mixture between the tips of two platinum wires 0.1 mm in diameter, spaced at 0.2 - 0.3 mm, dry briefly over an alcohol lamp and then heat in the flame until the drop of mixture spreads on both wire tips as a tiny bead. Taken out of the flame the bead cools right away and is then ready for use (the platinum wire electrodes can be soldered). Manufactured in this way thermistors age; they change their resistance at a fixed temperature with time. This ageing is faster during the first year. Thermistors can be aged artificially in a shorter period of time by cyclically changing their temperature under an electric current load.

Industrially-produced thermistors have a relatively small resistance value drift due to ageing.

Thermistors range considerably in size and shape, depending on their application. The same is true as far as their resistance is concerned (at a fixed temperature). Thermistor temperature sensors used in battery-driven bridge-configuration instruments range from one kΩ to a few kΩ. Those used in connexion with electronic signal converters may be in the tens or even hundreds of kΩ range.

High-resistance value thermistors are sensitive to liquid-water deposits on their surface. The water film provides a shunt resistance between the thermistor leads giving a false value of thermistor resistance and hence temperature. For this reason, thermistors should be laquered or have a protective glass cover.

The thermistor as a circuit element is always under an electric current load, producing heat inside the thermistor's body. If this heat is not efficiently dissipated by natural convection from the surface of the sensor, its temperature will be increased, leading to measurement errors.

In order to avoid the thermistor overheating, the load thereon should be kept below one milliwatt per square millimetre of its surface. A load of 1 - 2 mW mm^{-2} could increase the sensor temperature by 0.1°C.

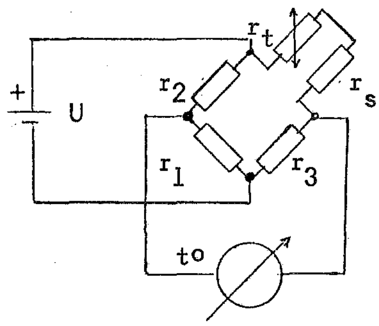


Figure 35 - Linearized thermistor thermometer

The Wheatstone out-of-balance bridge is a suitable signal converter for the thermistor thermometer. Because of the exponential response of the thermistor, additional linearization measures will be needed (Figure 35). Satisfactory linearization of the sensor's response, within a 30°C temperature range can be obtained through a series linearizing resistor, r_s, in the thermistor arm of the bridge. Suitably selected, r_s causes an inflection in the $I_{th} = f(t^o)$ graph and consequently a linear segment (see Part 3). Following the theory of the thermistor's linearization given, with a thermal coefficient of resistance of the sensor of four per cent per degree Celsius and a mid-scale point of 0°C, the value of the series resistor, r_s, can be determined from the relationship:

$$r_s = 0.7\ r_t$$

In order to cover the meteorological range of temperatures the thermistor thermometer needs several ranges, selectable by a range switch. As already mentioned, the ranges are controlled by separate resistors in the r_2 arm of the bridge. A series resistor, r_s, should be calculated for each range. The switch should be a "two-pole, multi-position" switch.

Remote sensing by the use of thermistor sensors presents no problems as regards the resistance of the connecting cables and the effect of temperature changes on them. Due to the high resistance of the sensor and its appreciable change of resistance due to the temperature change, the resistance of the leads can be ignored.

The settling time of the thermistor depends on its mass/surface area ratio and generally ranges from one to a few seconds.

Sources of error are:

- Instability of the bridge battery voltage;
- Thermistor parameter secular drift;
- Liquid water film "shunt" between thermistor leads;
- Drift in the values of the bridge components;
- Deviation from linearity of response of the instrument.

Other semiconducting temperature sensors include:

(a) <u>Germanium diodes</u>

The voltage drop (about 0.3 V) across a forward-biased germanium diode is dependent on the temperature of its junction (see Part 3). The change of this voltage drop as a result of temperature averages - 2.1 mV per 1°C.

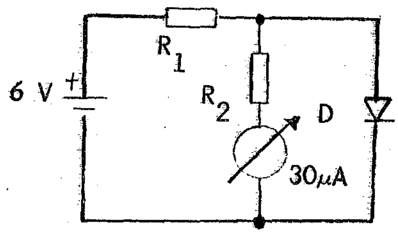


Figure 36 - Diode thermometer

A practical diode thermometer circuit is shown in Figure 36. The indicator comprises a sensitive microammeter in series with a resistor R_2. The calibration of this type of instrument is essentially linear. The diode sensor has satisfactory stability and a relatively short settling time.

The operational temperature for the germanium diode thermometer should not exceed 75°C;

(b) Germanium transistor temperature sensor

The semi-conductor triode's parameters are temperature-sensitive. The reverse saturation current, I_{co} (see Part 3), changes greatly with temperature. The transistor's collector current, I_c, being a function of I_{co} and the base current, I_b, also changes:

$$I_c = (1 + \beta)I_{co} + \beta I_b$$

where:

β = common emitter gain.

The absolute values of the reverse saturation current, I_{co}, are appreciably higher with germanium than with silicon transistors. This property is exploited in the germanium transistor thermometer shown in Figure 37.

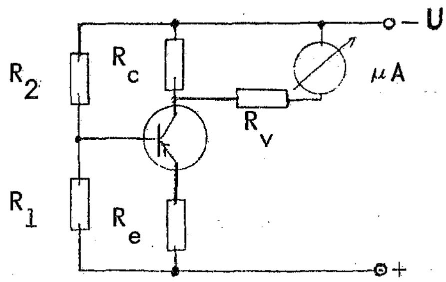


Figure 37 - Transistor thermometer circuit

The base current is held constant by the biasing voltage divider R_1 and R_2. As the reverse saturation current, I_{co}, varies with temperature, so does the collector current, I_c, causing the voltage drop across the collector load resistor, R_c, to vary. The variations in this voltage drop are indicated on a moving-coil microammeter in series with R_v and the dial may be calibrated directly in temperature. The scale is non-linear.

A possible application of this type of instrument is for a freezing-temperature warning relay.

3.2.5 Thermocouple temperature sensor

Conductors of two dissimilar metals, joined together as indicated in Figure 38 with their two junctions held at different temperatures, t_1 and t_2, generate a thermoelectric current. This phenomenon is known as Seebeck's effect (discovered in 1821).

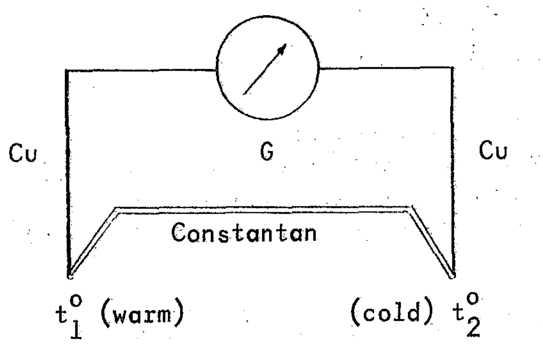


Figure 38 - Thermocouple

The electromotive force (e.m.f.) at the terminals of the thermocouple is proportional to the temperature difference ($t_1 - t_2$):

$$E = a(t_1 - t_2) \qquad (1)$$

where:

$a = dE/dt$, known as the Seebeck coefficient.

A more accurate expression, valid for a wider range of temperatures is:

$$E = a(t_1 - t_2) + b(t_1 - t_2)^2 \qquad (2)$$

For the meteorological range of temperatures equation (1) is quite satisfactory.

A number of metals and alloys are used in the form of wire as thermocouple material: platinum, copper, iron, tungsten, platinum-rhodium alloy (90% Pt + 10% Rh), constantan (40% Ni + 60% Cu), alumel (94% Ni + 6% Al), chromel (90% Ni + 10% Cr), tungsten-rhodium (26% W + 74% Rh), etc.

The e.m.f./°C of most thermocouples is in the microvolt range:

Copper/manganin	41×10^{-6} volt/°C
Manganin/constantan	41×10^{-6} volt/°C
Platinum/constantan	34×10^{-6} volt/°C
Iron/constantan	52×10^{-6} volt/°C

A number of thermocouple junctions connected in series is known as a thermopile (Figure 39).

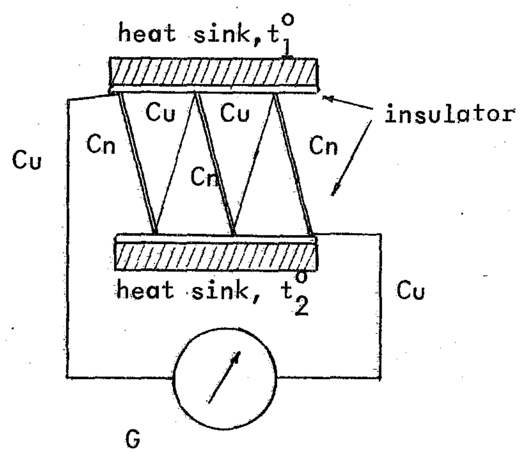


Figure 39 - Thermopile

Note : The thermocouple junctions are electrically insulated from the heat sinks. The e.m.f. of the thermopile is proportional to the number of thermocouple junctions.

A galvanometer is used as an indicator for a thermocouple or a thermopile. The efficiency of the combination of sensor and indicator is optimized by a resistance "matching" of the two:

$$r_t = R_g \tag{3}$$

where:

r_t = output resistance of the thermocouple;

R_g = internal resistance of the galvanometer.

This is obtain by the following reasoning:

The current, I, through the galvanometer may be expressed in terms of the e.m.f. of the thermocouple, E, and the resistance of the thermocouple, r_t, and galvanometer, R_g, as follows:

$$I = E/(R_g + r_t) \tag{4}$$

The voltage at the galvanometer terminals is:

$$V = R_g E/(R_g + r_t) \tag{5}$$

The electrical power delivered to the galvanometer will be:

$$P = I^2 R_g = E^2 R_g \frac{1}{(R_g + r_t)^2} = V.I \tag{6}$$

Maximum power will be delivered to the galvanometer (the case of the maximum sensitivity of the aggregate) by $dP/dR_g = 0$, thus:

$$\frac{E^2(R_g + r_t)^2 - 2R_g(R_g + r_t)}{(R_g + r_t)^2} = 0 \tag{7}$$

Consequently:

$$R_g^2 + 2R_g r_t + r_t^2 - 2R_g^2 - 2R_g r_t = 0 \tag{8}$$

and hence:

$$R_g = r_t, \tag{9}$$

which is the result in equation (3).

If the galvanometer is used as a millivoltmeter, the e.m.f. may be obtained through the measurement of V, based on the relationship:

$$E = V(R_g + r_t)/R_g \tag{10}$$

When using thermocouples one should keep in mind that they are measuring temperature difference. Stabilization of the cold junction in a thermostat at 0°C (melting ice) would give the actual temperature.

The signal from a thermocouple may be amplified by a differential amplifier, thus attaining a better sensitivity while using a less sensitive moving-coil indicator (far less susceptible to shock). The principles of such an instrument are illustrated in Figure 40. (For greater detail, see Part 3.)

The emitter-coupled difference amplifier shown in Figure 40 enables the amplification of the weak thermocouple signal applied to the bases of the transistors,

T_1 and T_2. The transistors are biased through the voltage dividers, R_1 and R_2. The amplified signal taken from the collector circuits of the transistors is fed into the indicator. The input signal causes an increase in collector current of the one transistor, and a corresponding decrease in the collector current of the other. The resulting difference in the voltage drops across the load resistors, R_c, and produces a voltage across the indicator, thus initiating a current through the indicator. The variable resistor, R_o, is the electrical zero adjustment potentiometer. With no temperature difference at the "hot" and "cold" junctions of the thermocouple, the input signal is zero and the output signal and thus the current through the indicator, should be zero.

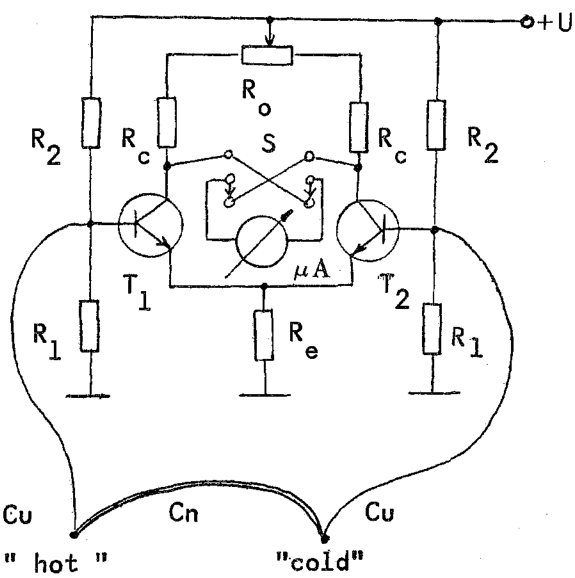


Figure 40 - Thermocouple with differential amplifier

The commutating switch, S, enables the polarity of the indicator to be reversed in the event of a reversal of the temperatures at the thermocouple junctions.

Difference amplifiers in an integrated circuit form make excellent amplifiers for portable low-power consumption thermocouple thermometers.

If actual temperatures rather than temperature differences are required, a stabilization of the cold junction at 0°C in a thermos flask is necessary. This inconvenience may be overcome by using a resistance bridge cold-junction temperature compensation (Figure 41). The change of resistance of R_t with changing ambient temperature creates an out-of-balance bridge potential, compensating for the "missing" cold junction.

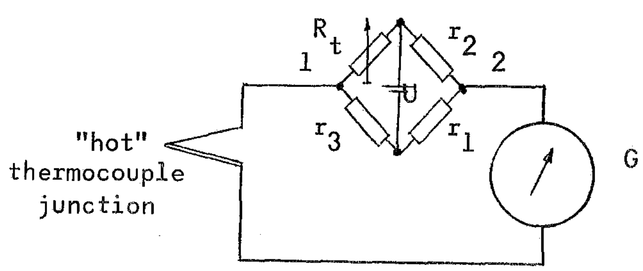


Figure 41 - Cold-junction bridge compensation circuit

It is to be noted that without the compensating bridge arrangement, the indicator would read the temperature difference between the hot junction and the terminals of the indicator itself.

3.3 Exposure of air-temperature measuring instruments - radiation errors

Air-temperature measuring instruments should be exposed to the ambient temperature in such a way as to facilitate the heat exchange between the thermometer and the environment, while keeping away radiation from the Sun or artificial sources of heat and wetting. A louvred wooden or plastic meteorological shelter is a satisfactory answer to these requirements.

Another solution is a double, or even triple, high-reflectivity metallic shield round the sensing part of the thermometer. The well-known Professor Baumbach thermometer shield is made of aluminium concentric hemispheres, allowing satisfactory natural ventilation of the sensor while reflecting any incident radiant heat.

Different temperature sensors vary in their susceptibility to errors from radiated heat. A general expression for the radiated heat temperature change is:

$$t - \Theta = Q/\beta$$

where:

$t - \Theta$ = the radiation error;

Q = the rate of absorbtion of radiant heat by the sensor;

β = the convective heat exchange, sensor/ambient air.

The above ratio depends on the physical parameters of the sensor and its ventilation.

Sources of radiation error, as far as meteorological screens are concerned, include the Sun, incandescent lamps used to illuminate the screen, the body heat of the observer, radiated heat from the ground and nearby objects and heat transfer through the material of the screen.

3.4 Settling time of thermometers

The response of a thermometer to a sudden change of temperature is such that in order to read the "true" new value of temperature, the thermometer needs a certain time to settle.

If the accuracy of the reading is pre-set and the magnitude of the temperature change is known, the time necessary for the settling of the thermometer can be found from the equation:

$$\tau = \lambda \ln \left[(t_o - \Theta/(t - \Theta)\right] \text{ seconds} \quad (1)$$

or using the common logarithm expression:

$$\tau = \lambda 2.3 \log \left[(t_o - \Theta)/(t - \Theta)\right] \text{ seconds} \quad (2)$$

where:

λ = lag-coefficient of the thermometer in seconds;

t_o = initial temperature

θ = new value of temperature;

t = temperature of the thermometer (the reading) after time (s).

In fact $(t_o - \theta)$ represents the temperature change (the "step") and $(t - \theta)$ is the temperature difference, (true value - thermometer reading), which is actually the accuracy of the temperature reading.

Equations (1) and (2) are obtained as follows:

The heat exchange between the thermometer and its environment is expressed by the equation:

$$dQ = -\beta S(t - \theta)d\tau \tag{3}$$

where:

dQ = heat exchange between thermometer and environment during time, d;

β = coefficient of convective heat exchange between thermometer and air;

S = surface area of the sensor;

t = temperature of the thermometer (the reading);

θ = ambient temperature.

The temperature change of the thermometer attributed to dQ is:

$$dt = dQ/mc \tag{4}$$

or, re-arranged:

$$dQ = mcdt$$

where:

m = mass of the sensor;

c = heat capacity of the sensor.

Combining (3) and (4) yields:

$$dt/d\tau = -(1/\lambda)(t - \theta) \tag{5}$$

where:

$\lambda = mc/\beta S$ (the lag-coefficient of the thermometer) (6)

Equation (5) accounts for the rate of change of the thermometer temperature.

With the ambient temperature, θ, constant, equation (5) can be further developed:

$$\int dt(1/(t - \theta)) = -(1/\lambda)\int d\tau \tag{7}$$

and the solution obtained in the form:

$$t - \theta = C\, e^{-(\tau/\lambda)} \tag{8}$$

With $\tau = 0$, $t = t_o$ and from (8) $C = t - \Theta$ is obtained, hence:

$$(t - \theta)/(t_o - \theta) = e^{-(\tau/\lambda)} \tag{9}$$

or taking the reciprocal value of (9) in order to remove the minus sign:

$$(t_o - \theta)/(t - \theta) = e^{\tau/\lambda} \tag{10}$$

If λ is made equal to τ, equation (10) yields:

$$(t_o - \theta)/(t - \theta) = 2.718... \tag{11}$$

By knowing the value of Θ and selecting a value of t_o higher than Θ, the time for the thermometer to reach the value of t, calculated from (11), gives the magnitude of the lag-coefficient, λ.

If natural logarithms are taken on both sides of equation (10), the following expression is obtained:

$$\ln\left[(t_o - \theta)/(t - \theta)\right] = \tau/\lambda \tag{12}$$

Equation (12) is equation (1) re-arranged.

A graphical representation of the response of the thermometer (Figure 42) enables the estimation of the value of the lag-coefficient, λ.

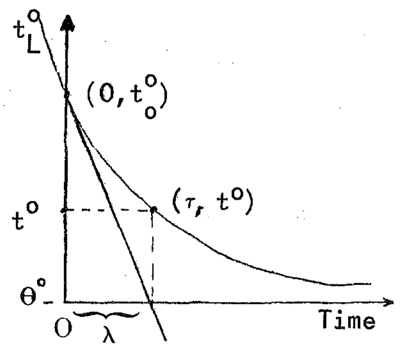


Figure 42 - Graphical evaluation of the lag-coefficient of a thermometer

λ is the time-span along the axis of the time co-ordinate between the zero of the co-ordinate system and the intersection point of the tangent to the graph in the point $(0,t_o)$ amd the time-axis. This graph is an illustration of the experimental measurement of the lag-coefficient of a thermometer, using a stop-watch. The procedure is as follows:

(1) Select a temperature, t_o, and heat the thermometer to a value slightly above this temperature;

(2) Let the thermometer cool naturally and start the stop-watch as the thermometer reaches the temperature t_o;

(3) Stop the stop-watch as the thermometer reaches the temperature, t, calculated from equation (11).

The time interval between the start and the stop of the watch is the lag-coefficient expressed in seconds.

Example of estimation of the settling time of a thermometer

Assume t_o = 30°C and Θ = 20°C and the lag-coefficient, λ = 100 s.

Find the time τ, for the thermometer to read the ambient temperature with an accuracy of 0.1°C, i.e. $(t - \Theta)$ = 0.1°C.

Since we have $(t_o - \Theta)$ = 10°C, applying equation (2) gives:

$$\tau = 100 \times \ln(10/0.1) = 100 \times 2.3 \times \log(10/0.1) = 460 \text{ s.}$$

Thus, it will take a time equivalent to nearly five times the lag-coefficient for the thermometer to approach within 0.1°C of the new ambient temperature after a step-change.

3.5 Calibration and testing of temperature-measuring instruments

Liquid-in-glass thermometers, regardless of the existence of a calibration certificate, should be tested at a few points on the scale in a thermometer calibration bath before issue to a field station. This is a precautionary measure, necessary with thermometers subjected to rough handling during transport and after prolonged storage.

On-site checking of station thermometers, using a portable working-standard thermometer during inspection tours, is recommended.

Laboratory re-calibration is necessary after repair (of a broken mercury column, for example), as well as when deviations in the readings compared with a reliable working-standard instrument are revealed. Re-calibration should be carried out using deep immersion techniques in a thermostatically controlled immersion chamber.

Results of the re-calibration should be entered in the certificate of the thermometer.

Thermographs are checked on a daily basis against the minimum and maximum thermometers. The clock-rate should be checked weekly against an accurate ordinary clock.

Laboratory re-calibration is necessary every two years, but more often if deviations in the temperature indications of the thermograph exceed 1°C. Re-calibration of the thermograph should follow any serious repair work.

Metal resistance thermometers should be checked against a standard instrument on a yearly basis.

Semi-conductor electrical resistance thermometers' calibration characteristics are not very stable, chiefly due to ageing of the sensor. Comparison with a reliable thermometer once a month is recommended.

When making comparisons, the effect of different lag-coefficients must be taken into account.

CHAPTER 4

MEASUREMENT OF ATMOSPHERIC HUMIDITY

4.1 Nature and units of measurement of absolute humidity, relative humidity and dew point - other humidity parameters

Water vapour is one of the components of the Earth's atmosphere. There are several ways to specify the amount of water vapour present in the air:

(a) Mixing ratio: $r = m_v/m_a$ (g kg^{-1})

As shown by the relationship this is the ratio of the mass, m_v, of water vapour to the mass, m_a, of dry air with which the water vapour is associated. The mixing ratio is measured as grams of water vapour per kilogram of dry air;

(b) Moisture content: $q = m_v/(m_v + m_a)$ (g kg^{-1})

Moisture content or specific humidity is defined as the ratio of the mass of water vapour, m_v, to the mass of moist air, $(m_v + m_a)$, with which it is associated. Moisture content can be expressed through the mixing ratio as:

$$q = r/(1 + r);$$

(c) Vapour pressure: e

Vapour pressure is the partial pressure of the water vapour as a gaseous component of the atmosphere. The pressure of the water vapour is measured in hectopascals. The relationship between the water vapour, e, and the mixing ratio, r, is:

$$e = rp/(0.622 + r) \quad \text{or} \quad r = 0.622e/(p - e)$$

where p = atmospheric pressure in hPa.

Similarly:

$$q = 0.622e/(p - 0.378e);$$

(d) Absolute humidity: $d = m_v/V$ (g m^{-3})

Absolute humidity is defined as the ratio of the mass of water vapour, m_v, to the volume, V, occupied by the moist air with which it is associated.

The relationship between the absolute humidity and the vapour pressure is:

$$d = 0.81e/(1 + 0.00366t) \quad (\text{g m}^{-3} \text{ for } e \text{ in hPa});$$

(e) Relative humidity: $U = (e/e_s) \times 100\ \%$

Relative humidity is the ratio of the actual vapour pressure, e, to the saturation vapour pressure, e_s, at the air temperature. Similarly:

$$U = (r/r_s) \times 100\ \%$$

where:

r_s = the saturation mixing ratio at the actual temperature of the air.

With temperatures below 0°C there are two values for saturation-vapour pressure:

e_{sw} = saturation-vapour pressure over water;

e_{si} = saturation-vapour pressure over ice;

and, correspondingly, two different expressions for relative humidity:

$$U_w = (e/e_{sw}) \times 100\ \%;$$
$$U_i = (e/e_{si}) \times 100\ \%.$$

For the purposes of operational meteorology, relative humidity at temperatures below 0°C is evaluated with respect to water (U_w). This has a number of advantages from an operational point of view;

(f) Dew point: t_d °C

Dew point is that temperature to which air has to be cooled at constant pressure to cause it to become saturated with respect to a water surface. The dew-point temperature is normally lower than, or equal to, the actual air temperature.

If the saturation is with respect to an ice surface, the temperature will be the frost point, t_f.

To summarize, the units of measurement of atmospheric humidity normally used are:

- Mixing ratio (g kg^{-1});
- Moisture content (g kg^{-1});
- Vapour pressure (hPa);
- Absolute humidity (g m^{-3});
- Relative humidity (%);
- Dew point and frost point (°C).

4.2 General principles of hygrometers

The methods for measuring air humidity in use for operational and research purposes fall into the following classes:

(a) Methods based on the change of dimension of a hygroscopic substance (hair, horn, gold-beater's skin, etc.);

(b) Electrical resistance methods (LiCl humidity resistor);

(c) Thermodynamic methods (psychrometers);

(d) Condensation method (dew point and frost point hygrometers);

(e) Diffusion method;

(f) Absorption method ($CaCl_2$ humidity absorption);

(g) Electrical capacitance method.

4.2.1 Humidity-measuring instruments based on change of dimension of hygroscopic substances - the hair hygrometer

A number of organic substances change their dimensions with a change in their moisture content. A change of air humidity usually affects the moisture content of such substances.

Human hair with the grease removed thoroughly has been used for relative humidity measurements since the seventeeth century (Saussure). Hair increases its length between 2 and 2.5 per cent on average for a change of 0 to 100 per cent relative humidity. Although the change of length varies with different types of hair, there is a fairly constant relationship between the relative humidity and the variations in the length of the hair. An idea of the hair's response to air humidity changes is given by the graph shown in Figure 43. The elongation of the hair is expressed as a fraction of the overall change of the length for a 0 - 100 per cent change in air humidity.

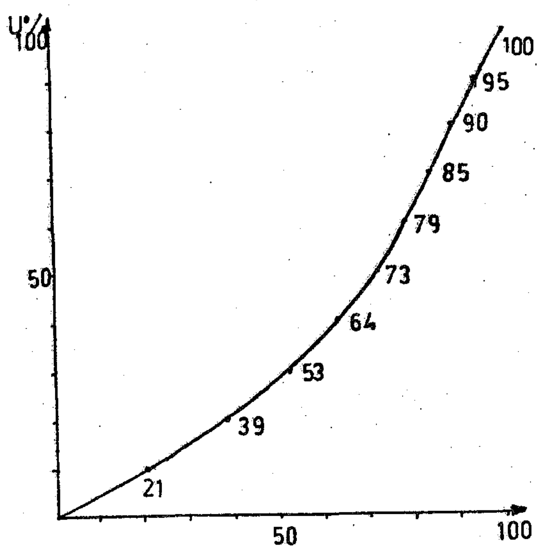


Figure 43 - Hair/air humidity response

As is evident from the graph, the hair's response to the humidity change is far from linear. According to Sreznevskii's theory, the relative change of the length of the hair, $\Delta l/l$ is a function of the logarithm of the relative humidity. The mechanism of the change of the dimension of the hair is thought to be caused by the forces of surface tension of the numerous water menisci of the water condensed inside the pores of the hair. The lag-coefficient of the hair depends on a number of parameters. It is found that $(dU/d\tau)/(U - U_f)$, where U = instantaneous (indicated) value of humidity, U_f = true value of humidity (final), depending on the temperature, on whether $dU/d\tau$ is positive or negative, on the tension of the hair, on its previous treatment and to a limited extent on the ventilation.

Spilhaus has suggested the following expression for the dependence of $dU/d\tau$ on U and $U - U_f$:

$$\left| \frac{1}{U} \cdot \frac{dU}{d\tau} \right| = k \left| (U - U_f) \right|^n$$

where: τ = time, k, n are constants depending on temperature, tension and all the above listed paramters. Especially unfavourable is the effect of temperature on the lag-coefficient, illustrated in the table below:

Time required for the sensor to indicate 63 per cent of a relative humidity change

Type of sensor	Temperature of the air					
	20°	10°	0°	-10°	-20°	-30°
	τ (s)					
Ordinary hair	30	40	55	175	400	800
Hair, rolled flat	10	10	12	15	20	30
Gold-beater's skin	6	10	20	50	100	200

One type of meteorological station hygrometer utilizes only one single hair as its sensor (Figure 44). The upper end of the hair (3) (which is usually 15 - 20 cm long) is glued to the zero-adjustment spring (1). The lower end of the hair is wound on a pulley (5) and held tight in position by the pull of a small weight (6) (about 5 g).

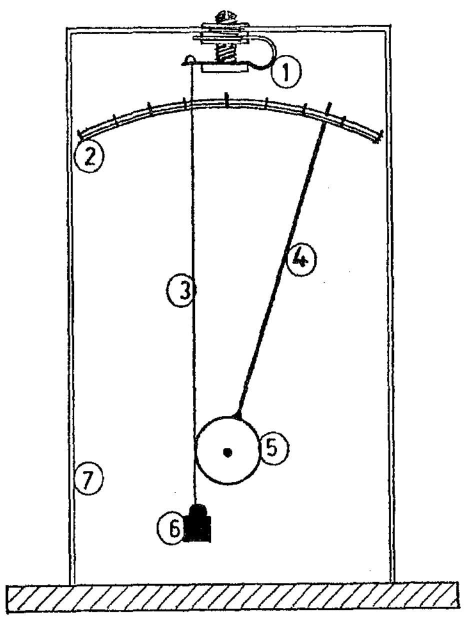


Figure 44 - Principle of hair hygrometer

As its length changes with variations in humidity, the hair turns the pulley and the pointer (4) affixed to it, thus indicating the relative humidity values on the scale (2) fixed to the frame of the instrument.

The hair sensor is very sensitive to pollution. Grease deposits from being touched by bare fingers, or exposure to an atmosphere polluted by exhaust fumes, render it useless as a hygrometer. Periodic cleaning of the hair, using a suitable solvent, such as ether, is recommended. Re-calibration of the instrument after cleaning is necessary.

A bundle of hair has the power to move the recording mechanism of a hygrograph.

Three types of hygrograph recording mechanism are shown in Figure 45. The simplest mechanism is (a), while (b) has definite advantages. Consider Figure 46 which represents schematically the arrangement in Figure 45 (b); the following relationship for the mid-point displacement Δx can be written:

$$\Delta x = \sqrt{L^2 - a^2} \tag{1}$$

where:

a = initial half-length of the hair bundle;

L = length of the bundle resulting from an increased relative humidity of the air.

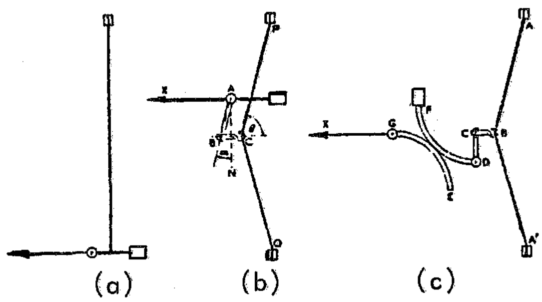


Figure 45 - Principle of hygrograph mechanism

If at 0% humidity $L = a$ and at 100% humidity the change of a is ΔL, the displacement of the mid-point will be:

$$\Delta x = \sqrt{L^2 - (L - \Delta L)^2} = \sqrt{2L\Delta L - \Delta L^2} \tag{2}$$

Substituting in (2) the value of ΔL which was mentioned earlier in this section to be 2.5% of L, we get:

$$\Delta x = (5L^2/100) - (6.25L^2/100^2) = 0.223L \tag{3}$$

With the arrangement in Figure 45 (a), the displacement of the free end of the bundle will be:

$$\Delta x = (2.5/100) \times 2 \times L = 0.05L \tag{4}$$

or about four times less than with the arrangement in Figure 45 (b).

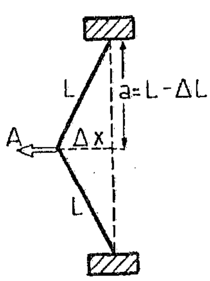


Figure 46 - Mid-point hair-bundle connexion

The main disadvantage of the system described is that the scale is rather irregular with a pronounced departure from linearity. One remedy for this is the arrangement shown in Figure 45 (c) which is incorporated in the U.K. Meteorological Office hair hygrograph (Figure 47).

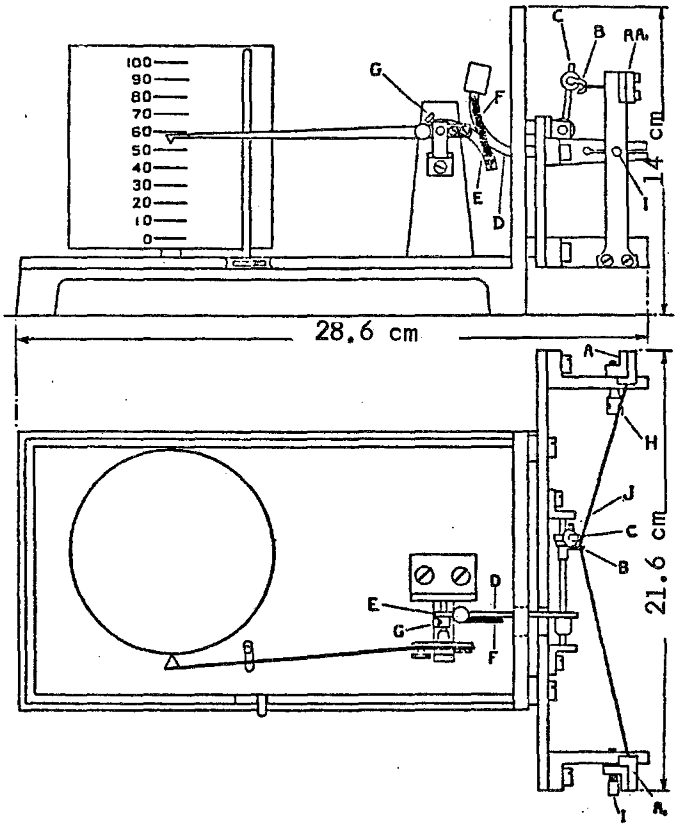


Figure 47 - Elevation and plan of a hair hygrograph

The scale-linearizing mechanism, which is also a mechanical amplifier, consists of two metallic quadrants - transmitting (DF) and receiving (GE). The transmitting quadrant is pivoted at D, its angle of rotation being a function of the hair-bundle mid-point displacement. The receiving quadrant, pivoted at G, carries the pen arm. The two quadrants being in contact with each other form a variable transmission ratio device. The curvature of the quadrants is selected so as to "straighten" the response of the hair-bundle to humidity changes.

The hygrograph, like many station recording instruments, has an ink-on-paper chart recorder. The chart is carried on a clock-driven drum of similar design to that of the barograph and thermograph.

The hair hygrometer and hair hygrograph are compared daily with a psychrometer. Good instruments are capable of measuring the relative humidity at positive temperatures with an accuracy of ± 5%.

As previously mentioned, re-calibration is necessary after the hair has been cleaned. The frequency of cleaning procedures is determined locally, depending on the amount of pollution.

Sources of error are:

(a) Change of the zero: usually, this is a result of the hair being overstretched because of rough handling. The overall sensitivity and accuracy of the instrument are affected as well;

(b) Grease, dirt and dust deposits on the hair: worsening of the hair's hygroscopic properties due to air pollution or improper handling leads to a deterioration in sensitivity and accuracy;

(c) Effect of temperature on lag-coefficient: negative temperature lag-coefficient, increasing with a fall of temperature is a major source of error.

4.2.2 The organic membrane hygrometer

Another mechanical air-humidity sensor is the gold-beater's skin membrane. This is an organic membrane of 10 - 20 mm thickness obtained from the gut of domestic animals.

A change of dimension of about 4.8 per cent over the 0 - 100 per cent humidity interval is one advantage of gold-beater's skin over hair. Higher sensor power, better linearity of response and smaller lag errors are other positive features of the membrane as a humidity sensor.

The organic membrane sensor measures the relative humidity of the air. With greater sensor power, a potentiometric signal converter can be used for a remote reading. This combination of sensor and signal converter is used in aerological measurements of humidity (radiosonde).

The sources of error in measuring air humidity with the organic membrane sensor are the same as those with hair.

4.2.3 The electrical resistance hygrometer

The electrical resistance hygrometer utilizes the variation of resistance of a thin hygroscopic film of lithium chloride (LiCl) with changes in the relative humidity of the air. The sensor is used in a bridge circuit fed by an alternating current source, thus avoiding polarization of the salt.

Lithium chloride sensors display hysteresis, especially when changing from higher to lower humidity values. They are temperature-sensitive, with a lag-coefficient increasing as the temperature decreases, but possess poor stability of calibration characteristics.

4.2.4 The psychrometer

The partial pressure of water vapour can be measured by a thermodynamic method making use of two thermometers; one measuring the air temperature and the other the temperature of an evaporating water surface. The thermometric pair is known as a psychrometer. In the main, two alternative psychrometer designs are in use in meteorology; the free-ventilated (August) psychrometer (Figure 49) and the forced-ventilation (Assmann) device (Figure 50). The so-called "sling psychrometer" (Figure 48) is still in use in some Meteorological Services, but is fast becoming obsolete. In its simplest form, the free-ventilation psychrometer consists of two similar thermometers, capable of reading the temperature to an accuracy of 0.1°C. The bulb of one thermometer, which may be of tubular form, is covered by a finelywoven muslin, cotton or rayon, which is kept moist with pure water. The thermometers are known as wet- and dry-bulb thermometers.

The drier the air the faster the evaporation from the moist covering and the larger the temperature difference between the dry- and wet-bulb thermometers. With an actual water-vapour pressure equal to the saturation-vapour pressure at the air temperature, both wet- and dry-bulb thermometers will read the air temperature.

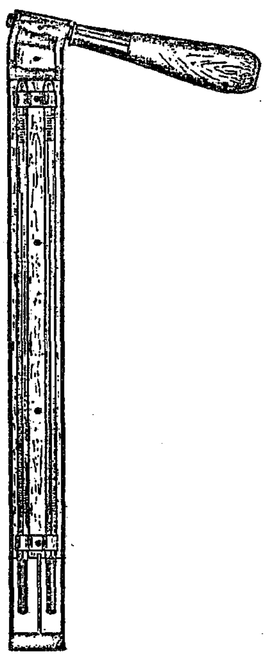


Figure 48 - Sling psychrometer

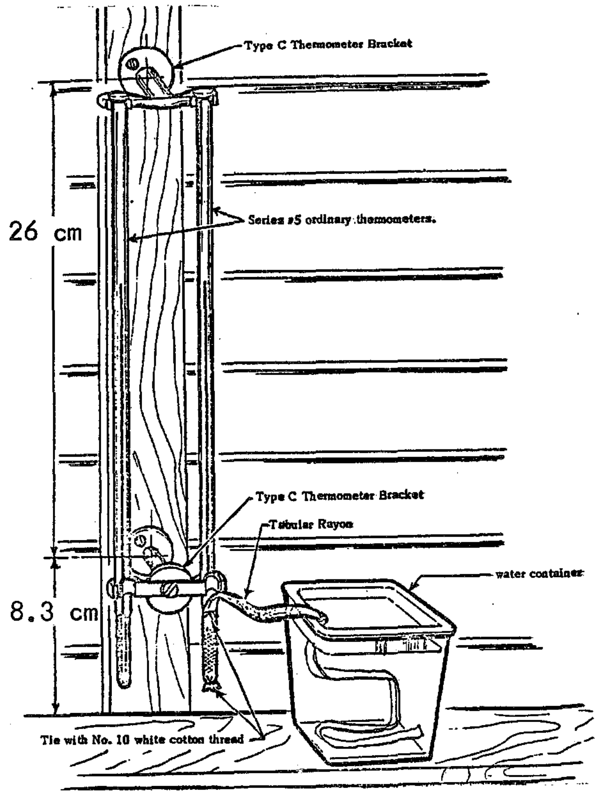


Figure 49 - August psychrometer

The actual water-vapour pressure can be obtained by measurement with the psychrometer from the following formula:

$$e = e_w - A(t_d - t_w)P \tag{1}$$

where:

e = actual water-vapour pressure;

e_w = saturation-vapour pressure over water at the wet-bulb temperature;

A is a constant depending, inter alia, on the ventilation rate;

t_d = the dry-bulb temperature in °C;

t_w = the wet-bulb temperature in °C;

P = atmospheric pressure in hPa.

The psychrometric formula under (1) can be derived on the basis of Dalton's law of evaporation:

$$M = \frac{cS(e_w - e)}{P} \tag{2}$$

where:

M = mass of water evaporated in unit time;

S = the surface area of the evaporating surface;

P = atmospheric pressure;

e_w = saturation-vapour pressure at the temperature of the evaporating surface;

e = the actual water-vapour pressure;

c = the proportionality constant.

Considering the heat lost through evaporation from the surface of the wet-bulb thermometer, by inserting the latent heat of evaporation of water, r, in equation (2), we obtain the expression:

$$Q_1 = \frac{crS(e_w - e)}{P} \qquad (3)$$

Because of the fall of temperature of the wet bulb a transfer of heat from the ambient air to the wet bulb takes place according to the relationship:

$$Q_2 = BS(t_d - t_w) \qquad (4)$$

where:

B = another proportionality constant;

the other entities as before.

When a state of equilibrium is reached, $Q_1 = Q_2$ and from equations (3) and (4) the following expression is obtained:

$$e = e_w - \frac{B(t_d - t_w)P}{cr} \qquad (5)$$

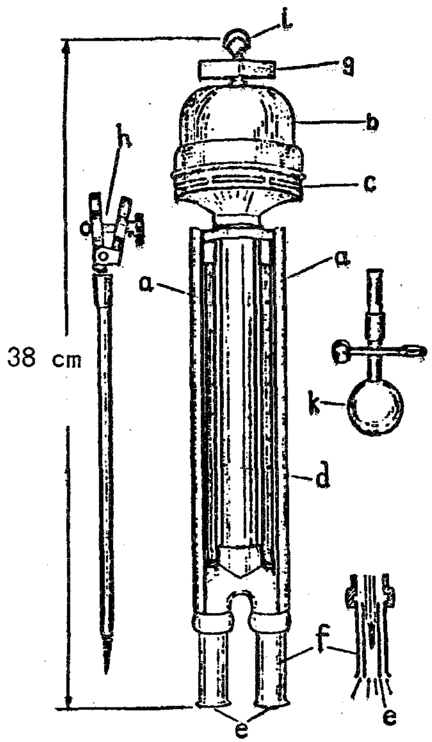
If the relationship $B/cr = A$ is substituted in equation (5) the psychrometric equation is obtained in its customary form.

Formula (1) is usually tabulated for fixed values of A and P. The values for e are obtained as a function of the pair of values of t_d, t_w and of e_w. For the range of negative temperatures, two sets of values for e are obtained, depending on whether the value of saturation-vapour pressure is taken with respect to water surface or an ice surface, e_w or e_i.

As well as values of vapour pressure, the corresponding values of relative humidity and dew point are also given in psychrometric tables. These tables facilitate the determination of humidity variables.

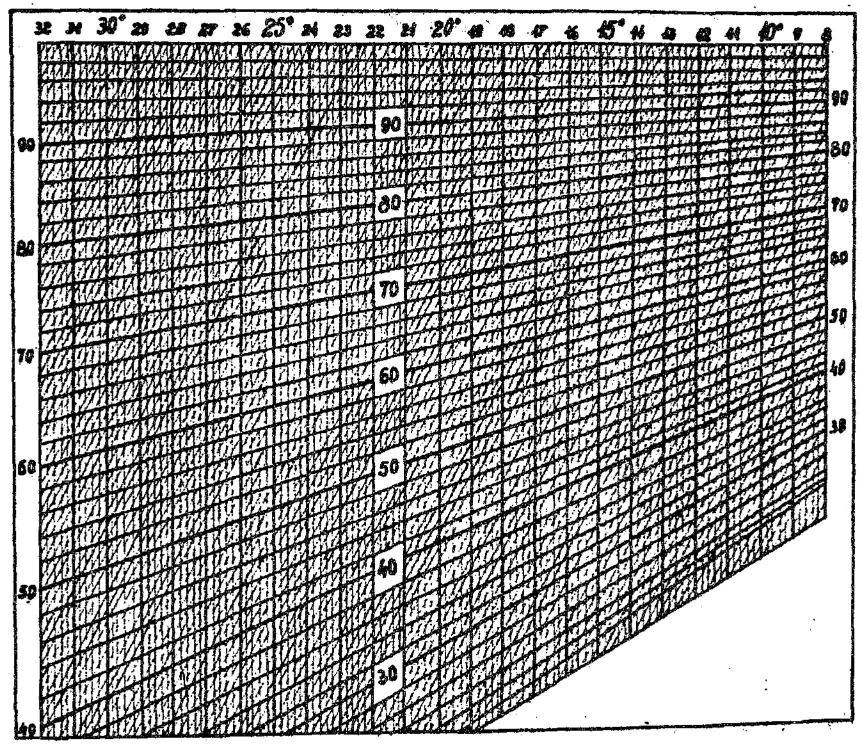
The psychrometric formula can also be presented in a nomographic form. One such nomogram is shown in Figure 50 (b). Wet- and dry-bulb temperatures are read on the single temperature scales along the abscissa at the top of the diagram of Figure 50 (b). The wet-bulb temperature is found first and the corresponding slant line on the nomogram is followed until its intersection with the vertical line corresponding to the dry-bulb temperature on the same scale. The intersection point gives the relative humidity on the ordinate at the left-hand side of the nomogram.

The nomogram is calculated from equation (1) assuming a ventilation rate of 2.5 m s^{-1}.



a - Thermometers
b - Dome containing clockwork
c - Fan and air outlets
d - Main air duct
e - Air inlets
f - Polished tubes protecting thermometers
g - Key for winding clockwork
h - Clamp for supporting the instrument
i - Point of support of the instrument; the clamp holds the ball securely but allows the instrument to hang vertically
h - Injector for wetting muslin of wet bulb

(a)



(b)

Figure 50 - (a) Assmann psychrometer and (b) psychrometer nomogram

The readings of the psychrometer are sensitive to the rate of ventilation. The values of A versus ventilation rate are given below:

A	0.00130	0.00090	0.00078	0.00071	0.00067
w (m s^{-1})	0.12	0.50	1.00	2.00	4.00

Of the two psychrometer types - free-ventilation and forced-ventilation - the latter gives the more reliable results owing to the consistency of its ventilation rate.

The free- or naturally-ventilated psychrometer is installed inside a meteorological screen using a special thermometric stand with a container for distilled water attached to it. The wet-bulb wick hangs down into the water and keeps the wet bulb moist by capillary action along the wick.

The aspirated psychrometer, which is normally kept in a specially fitted wooden box when not in use, is suspended out of doors from a hook for the purpose of taking measurements. Although the instrument is protected from radiation, the exposure site should be away from radiation sources (e.g. brick or concrete walls exposed to the sun, the observer himself).

If a strong wind is blowing, the psychrometer's aspirator should be shielded from its effect by the special sheet-metal semi-circular shield provided with the instrument.

Errors in the estimation of the wet-bulb depression will lead to errors in the determination of the absolute and relative humidity of the air.

The following possible sources of error should be considered in connexion with measurements made with psychrometers:

(a) The uncertainty of the formation of an ice bulb at temperatures below 0°C: the value of e_w in equation (1) will be different for the same negative wet-bulb temperature depending on the state of the water on the wet bulb:

Saturation-vapour pressure

Temperature (°C)	0	-2	-4	-6	-10	-15	-20
Over ice, e_i	6.11	5.18	4.39	3.70	2.62	1.67	1.05
Over water, e_w	6.11	5.27	4.54	3.90	2.86	1.91	1.25

(b) The accuracy of the psychrometric method decreases with increasingly negative temperatures because of the diminishing value of the difference $t_d - t_w$:

t^{o} C	-30	-20	-10	0	10	20	30
$\frac{\Delta U}{U}$ %	18	8	4	2	1	1	1

(c) The effect of variations in the ventilation rate should be considered, especially with the August psychrometer (free ventilation). It has been found that a change in wind speed outside the screen over the range 0.3 - 4.0 m s^{-1} can lead to an error of 7 per cent in the humidity measurement.

The following table gives an idea of the variability of the screen ventilation rate due to a change in wind speed outside the screen:

Inside, w m s^{-1}	0.38	0.47	0.51	0.66	0.79	1.08	1.43
Outside, w m s^{-1}	0.80	1.26	1.67	2.13	2.66	3.22	4.21

(d) The wet-bulb temperature is affected by the presence of dissolved matter in the water as well as grease on the wick. This leads to errors in the determination of the air humidity. Distilled water only should be used for the purpose of wetting the wet bulb. The wet bulb covering and wick should be changed regularly.

4.2.5 Remote-reading and recording psychrometers

The use of electrical temperature sensors such as 100-ohm platinum resistance thermometers or thermistors as wet- and dry-bulb thermometers facilitates the remote reading of air humidity by means of a psychrometer. The electrical output of the sensors can also be recorded.

Direct recording of relative humidity through psychrometric measurements entails conversion of the psychrometric data into a suitable form. The machine conversion of the data requires quite sophisticated electronic equipment.

A suitable relationship for a "direct calculation of the value of relative humidity from t_d and t_w values is proposed by Rotschen (Reinrechnerische Bestimmungen der Zustandwerte feuchter Luft nur aus t_{tr} und t_f - Klimatechnik, Nr. 7, 1966):

$$U\% = \frac{A(t_w) + t_w - t_d}{A(t_d)} \times 100 \qquad (1)$$

where:

$$A(t_i) = 0.147 \times 10\ (\frac{t_i}{31.6 + 0.1345t_i} + 1.79435)$$

The function $A(t_i)$ can be pre-calculated for the range of meteorological temperatures and the values stored in the memory of the instrument. The relative humidity is obtained using the psychrometric data and the correspoonding values of $A(t_i)$ by means of equation (1).

Being essentially a temperature-measuring instrument, the psychrometer or more specifically, its thermometers, are subject to the same maintenance, testing and calibration schedules as all thermometers. (See Chapter 3.)

In addition, periodic checks of the condition of the wet-bulb covering and wick as well as the aspirating device in the case of Assmann-type psychrometers, are essential.

Changes in the properties of the wet-bulb covering and wick owing to pollution may affect the magnitude of the wet-bulb depression and hence the accuracy of the measurement.

An even more crucial effect on the instrument's accuracy is a change in the rate of aspiration of the wet- and dry-bulb thermometers. Most often a deterioration in the performance of the aspirator is caused by congealed lubricant in its gear-train.

The periodic check of the constancy and magnitude of the rate of aspiration should be made on a yearly basis, followed by cleaning and lubrication of the gear if necessary.

4.2.6 The dewcel

The principle of operation of the dewcel can be readily understood by referring to Figure 51.

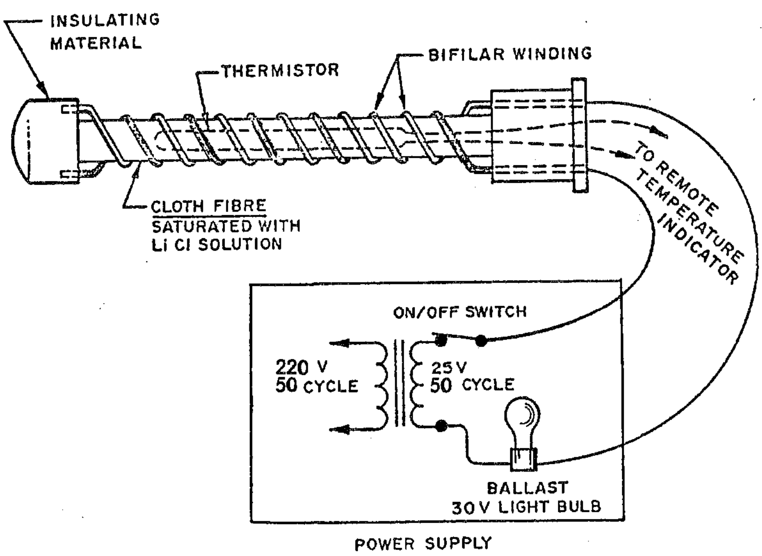


Figure 51 - The dewcel

The lithium-chloride dewcel sensor consists of an electrically-insulated tube wrapped around with glass-fibre tape. The tape is soaked in an aqueous solution of lithium chloride. A bifilar winding of gold-plated wire is laid over the tape with equal spacing between the turns. An electrical a.c. source is connected to the ends of the bifilar winding and a remote reading thermometer element (100-ohm platinum resistance thermometer or thermistor) is positioned inside the sensor tube.

Being an electrolyte, the LiCl solution is electrically conducting. A current, the size of which depends on the concentration of the solution, is passed through it between adjacent bifilar electrodes. The current causes an increase of temperature in the sensor and a resulting evaporation of water from the solution.

As the concentration of the solution increases, its conductivity decreases and less current flows, resulting in less heating. Water vapour from the air is absorbed into the solution, which is strongly hygroscopic, reducing the concentration and increasing the conductivity and hence the heating current. An equilibrium point is reached where the rate of evaporation is balanced by the rate of asborption and the temperature at which this equilibrium is reached depends on the amount of water vapour in the air. At the equilibrium temperature, the water-vapour pressure over the surface of the sensor (solution) becomes equal to the water-vapour pressure in the ambient air. A different equilibrium temperature is reached at a different water-vapour pressure in the atmosphere.

The relationship between the equilibrium temperature, measured by the thermometric element of the sensor, and the air-humidity characteristic, the dew point, are presented in a tabular form; thus, by measuring the first, the second is obtained. In some instruments the sensor thermometer is calibrated directly in dew-point temperature.

The current through the sensor is controlled automatically through the change of the electrical conductivity of the electrolyte due to its change of concentration by the water-evaporation process.

The curve showing the relationship between equilibrium temperature T^o_{eq}, and the dew point T^o_{dew} is a straight line (Figure 52).

The theory of the sensor reveals that its performance strongly depends on ventilation, technical design parameters (interelectrode distance, tape/electrolyte relation), as well as electrode voltage:

$$\frac{m_{vp}}{S} = \frac{l^2(T_{eq}-T_a)\ (a_1 + a_2 + a_3S'/S)}{\chi \cdot v_o \cdot k_3^2\ \ A' \cdot U_o^2\ (1 + \beta \cdot T_{eq})}$$

where:

m_{vp}/S = mass of water vapour per unit surface of the sensor capable of being absorbed from the air at a temperature difference (T_{eq} - T_a). (This is a measure of the transient processes' duration by a change in the atmospheric humidity.);

l = interelectrode distance;

T_{eq} = equilibrium temperature;

T_a = air temperature;

a_1 = coefficient of thermal radiation;

a_2 = coefficient of convection;

a_3 = coefficient of heat conduction of glass-fibre tape;

S' = cross-section of area of the sensor;

S = surface area of the evaporating surface of the sensor;

χ = initial specific electrical conductivity of the electrolyte;

v_o = initial volume of the moisture-sensitive layer;

k_3 = coefficient accounting for the ratio of the fibre material to electrolyte in the cross-section of the sensor;

A' = heat equivalent of the electrical energy;

U = voltage between the bifilar electrodes;

β = coefficient accounting for the temperature change of the electrical conductivity of the electrolyte.

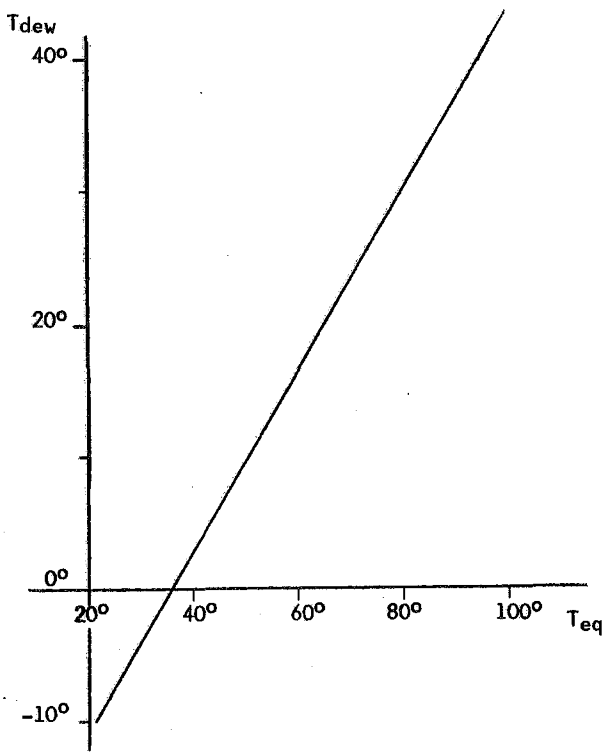


Figure 52 - The dewcel calibration curve

The dewcel is in wide-spread use in industrial applications as well as being a meteorological sensor. Users, however, should keep in mind its many deficiencies:

- Sensitivity of the sensor to ventilation;
- Sensitivity to pollution;

- Necessity for a continuous heating current (with no heating current, the LiCl solution tends to deliquesce and drip away);
- Necessity for periodic cleaning of the tape and replenishing of the electrolyte;
- Higher (about 98°C) and lower (about -45°C) temperature threshold of operation;
- Low relative-humidity limit.

At the meteorological station, the dewcel sensor is usually installed inside the Stevenson screen. A special ventilated duct, built in such a way as to prevent precipitation from directly reaching the sensor, allows the sensor to be in contact with the ambient air. The ventilator should be left running continually if possible. Otherwise, ventilation should be started at least 20 minutes before actual time of observation.

The heating of the dewcel element is maintained continuously throughout the operational life of the cell. Special care should be taken in order to prevent occasional, accidental switching-off of current to the sensor.

Sources of error are:

- Atmospheric pollution - dirty sensor;
- Direct effect of precipitation on the sensor;
- Errors in the temperature measurement of equilibrium temperature;
- Change in the chemistry of the electrolyte at low (-10° to -20°C) negative temperatures;
- Loss of electrolyte by power failure or switching-off of the sensor.

Dewcel measurements are checked against psychrometer readings. While small fluctuating deviations from the psychrometer readings may be considered acceptable, a steady deviation, increasing with time, is an indication of the need for cleaning and re-activating the sensor.

CHAPTER 5

MEASUREMENT OF SURFACE-WIND DIRECTION AND SPEED

5.1 Wind direction and wind speed - specific features - units of measurement

Wind velocity is a vector quantity having direction and magnitude (a scalar quantity known as speed). The wind velocity is considered in terms of three components, two of them lying in a plane parallel to the Earth's surface, the third perpendicular to that plane. For most operational meteorological purposes, the vertical component is disregarded, thus surface wind is considered as a two-dimensional vector quantity.

Wind velocity is subject to variations, both in period and amplitude. This is because the airflow known as wind is not laminar. The wind over the surface of the Earth is a turbulent flow, comprising eddies of differing sizes and physical parameters travelling with the flow. The Earth's orography is the main factor determining the turbulent structure of the wind. This structure of the airflow manifests itself through the so-called "gustiness" of the wind, i.e. fluctuations of the surface-wind parameters.

For most purposes, the mean wind velocity is taken as an average of instantaneous values over a ten-minute interval. A numerical expression for the wind speed variability can be obtained through the gustiness factor, G:

$$G = \frac{v_{max} - v_{min}}{v_{mean}}$$

where:

v_{max} = maximum wind speed;

v_{min} = minimum wind speed;

v_{mean} = mean wind speed.

All three scalar speed quantities are taken over a time period of ten minutes.

The wind speed may be indicated in any one of the following units:

(a) Knots (nautical miles per hour), abbreviated: kt;

(b) Metres per second: m s^{-1};

(c) Kilometres per hour: km h^{-1};

(d) Miles per hour: m.p.h.;

(e) Feet per second: ft s^{-1}.

For the purposes of international exchange of meteorological information wind speed is reported in metres per second (m s^{-1}) or knots (kt). The relation between the various wind-speed units is given in the following table:

kt	$m\ s^{-1}$	$km\ h^{-1}$	m.p.h.	$ft\ s^{-1}$
1.000	0.515	1.853	1.152	1.689
1.943	1.000	3.600	2.237	3.281
0.868	0.447	1.609	1.000	1.467
0.540	0.278	1.000	0.621	0.911
0.592	0.305	1.097	0.682	1.000

In addition to the units tabulated above, wind speed may be indicated in Beaufort units. The Beaufort scale makes use of familiar, natural phenomena connected with different wind speeds. That part of the Beaufort scale which relates to estimating wind speed over land is given on page 84.

Wind direction is indicated in degrees measured from true north in a clock-wise direction. The direction of the wind refers to the direction from which the wind is blowing.

For the purpose of international exchange of data the wind direction is reported in degrees to the nearest ten degrees.

Another wind-direction scale is based on compass points (8, 16 or 32 points according to to the accuracy required). The following abbreviations are used to indicate the compass points:

Compass direction	Equivalent in degrees	Sector in degrees	Compass direction	Equivalent in degrees	Sector in degrees
N	360	355-5	S	180	175-185
N'E	11.25	6-16	S'W	191.25	186-196
NNE	22.50	17-28	SSW	202.50	197-208
NE'N	33.75	29-39	SW'S	213.75	209-219
NE	45.00	40-50	SW	225.00	220-230
NE'E	56.25	51-61	SW'W	236.25	231-241
ENE	67.50	62-73	WS'W	247.50	242-253
E'N	78.75	74-84	W'S	258.75	254-264
E	90.00	85-95	W	270.00	265-275
E'S	101.25	96-106	W'N	281.25	276-286
ESE	112.50	107-118	WNW	292.50	287-298
SE'E	123.75	119-129	NW'W	303.75	299-309
SE	135.00	130-140	NW	315.00	310-320
SE'S	146.25	141-151	NW'N	326.25	321-331
SSE	157.50	152-163	NNW	337.50	332-343
S'E	168.75	164-174	N'W	348.75	344-354

The Beaufort scale of wind force for reporting surface wind

Beaufort number	Descriptive term	Wind speed equivalents Knots	$m\ s^{-1}$	Specifications for observations over land
0	Calm		0-0.2	Calm; smoke rises vertically
1	Light air	1-3	0.3-1.5	Direction of wind shown by smoke drift but not by wind vanes
2	Light breeze	4-6	1.6-3.3	Wind felt on face; leaves rustle; ordinary vanes moved by wind
3	Gentle breeze	7-10	3.4-5.4	Leaves and small twigs in constant motion; wind extends light flag
4	Moderate breeze	11-16	5.5-7.9	Raises dust and loose paper; small branches are moved
5	Fresh breeze	17-21	8.0-10.7	Small trees in leaf begin to sway; crested wavelets form on inland waters
6	Strong breeze	22-27	10.8-13.8	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty
7	Near gale	28-33	13.9-17.1	Whole trees in motion; inconvenience felt when walking against wind
8	Gale	34-40	17.2-20.7	Breaks twigs off trees; generally impedes progress
9	Strong gale	41-47	20.8-24.4	Slight structural damage occurs (chimney pots and slates removed)
10	Storm	48-55	24.5-28.4	Seldom experienced inland; trees uprooted; considerable structural damage occurs
11	Violent storm	56-63	28.5-32.6	Very rarely experienced; accompanied by widespread damage
12	Hurricane	64 and over	32.7 and over	

Note: The equivalents refer to a standard height of 10 metres above open, flat ground.

5.2 Principles of wind-measuring instruments

5.2.1 Sensing the wind direction - the wind vane - mechanical, electrical potentiometric, selsyn signal converters

The wind vane consists of a metal sheet of rectangular (or other suitable) form fastened to a metal rod, pivoted and capable of rotating around a vertical axis with a minimum of friction. The weight of the metal sheet is balanced by a metal counter weight at the other end of the rod (Figure 53 (a)). Instead of one, two metal sheets may be fastened together at an angle to the rod; a splayed type of wind vane (Figure 53 (b)). There are other types of wind vane shown in the figure but those at (a) and (b) are the most frequently used. Because the wind pressure is applied at the metal sheet to the leeward of the pivot axis, the wind vane tends to orient itself so that it is pointing toward the direction from which the wind is blowing.

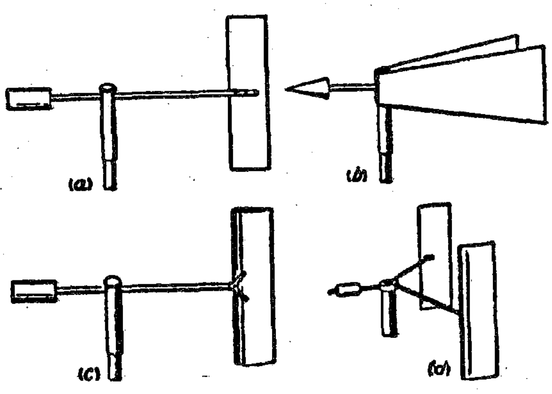


Figure 53 - Types of wind-vane

The wind vane is a second-order system and it tends to overshoot and oscillate about its true position. Special measures are taken to make the wind vane nearly aperiodic. One way to attain this is to introduce viscous dynamic friction through the use of special hydraulic dampers. The optimum damping ratio is less but close to 1.0. Overdamping (damping ratio over 1.0) makes the wind vane's response to wind-direction changes sluggish (see Guide to Meteorological Instruments and Methods of Observation (WMO-No. 8), section 6.3).

The following general equation gives the relationship between the various physical quantities responsible for the behaviour of the ordinary wind vane:

$$L.S.v^2.\rho.f(a) = M_f + M_l$$

where:

- L = effective length of the rod of the wind vane;
- S = surface area of the metal sheet;
- v = wind speed;
- ρ = density of air;
- $f(a)$ = a quantity which is a function of the angle of attack of the wind vane in relation to the wind vector;
- M_f = moment created by the force of friction;

M_l = moment created by inertia.

The following characteristics of the wind vane are considered desirable:

- Minimum friction in the pivot;
- Centre of gravity of the wind vane coinciding with the centre of rotation (statically-balanced wind vane);
- Maximum wind torque and a minimum moment of inertia;
- Sufficient damping to make the wind-vane response nearly aperiodic;
- Durable design, capable of preserving the sensing characteristics of the wind vane up to hurricane speed.

The operational requirements concerning the wind vane may be summarized as follows:

- Wind-speed operating range: 0.5 to 50 m s^{-1};
- Resolution: 2^o - 5^o;
- Damping ratio: near but below 1 (0.3 to 0.7 allowable).

The period of oscillation of the wind vane depends on the wind speed in an almost inverse proportion.

The wind vane is used in connexion with one of various different signal converters. Two types of wind-direction signal converter are in predominant use in remote-reading conventional anemometers: the three-tap circular potentiometer (Figures 54 and 55) and the selsyn shaft angle transducer (Figure 56).

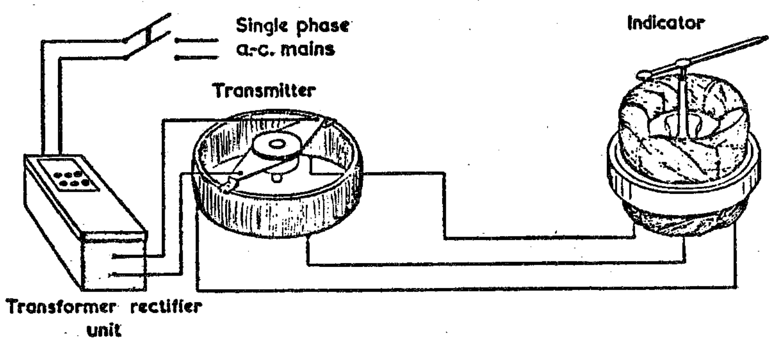


Figure 54 - Three-tap potentiometer system of remote indication

The three-tap potentiometer has two sub-assemblies: a transmitter, the ring potentiometer itself and a receiver, a three 120^o coil wound stator with a permanent magnet rotor.

The ring potentiometer is fed by a 12-volt rectifier through a twin-contact sliding contactor fastened to the wind-vane axis. Depending on the position of the sliding contactor in relation to the three taps on the potentiometer, the three coils of the stator in the receiver are fed by currents, the combined action of which gives rise to a magnetic field in the stator with south and north poles exactly corresponding to the position of the sliding contactor on the potentiometer. The permanent magnet rotor interacting with the stator magnetic field is oriented in the same way as the contactor. An indicating needle is fastened to the rotor and the direction of the wind vane is read out on a dial. The rotor/indicating needle system follows exactly the movement of the wind vane.

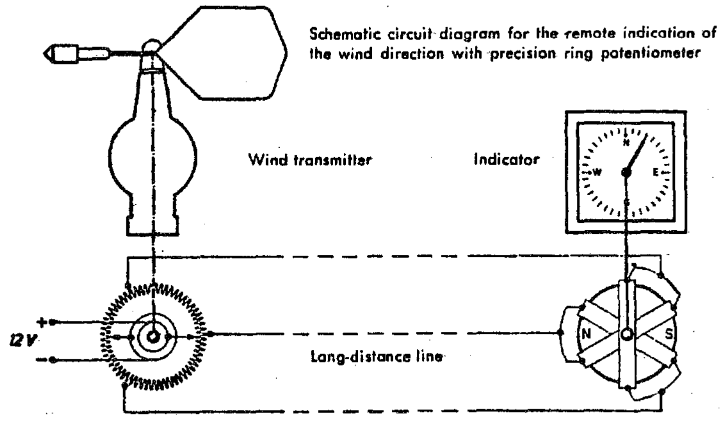


Figure 55 - Circuit diagram of ring-potentiometer assembly

The advantages of the three-tap potentiometer as a signal converter are its simplicity of design and installation. Its shortcomings: rapid wear of the potentiometer and relatively small torque of the permanent magnet/stator system of the indicator.

The resistance of each one of the three lines of the long-distance cable of the device is limited to a value specified by the manufacturer. This imposes certain limitations on the distance between the vane and the indicating (recording) device (about 1 500 m with certain designs).

Care should be taken with the remote-reading three-tap device installation not to interchange the connexions of the three leads of the cable at either the vane or indicator end. Crossed connexions would result in a gross error in the wind-direction indiction.

The selsyn shaft angle signal converter is a more modern remote-reading system. Its principle is illustrated in Figure 56.

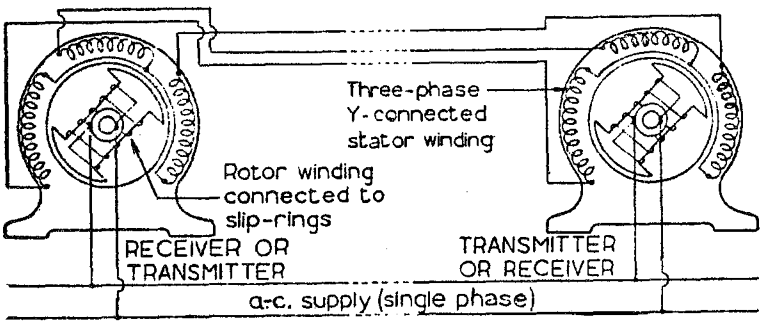


Figure 56 - Principle of selsyn system

The transmitter and receiver of the selsyn system have an exactly similar construction. They both have a three-phase motor-like stator winding and a bi-polar rotor winding. The stator windings of the transmitter and receiver are mutually connected by a three-lead cable as shown in the figure. The rotor windings are fed in parallel by an a.c. source (a.c. voltage may be 24 or 115 V depending on the manufacturer). The rotor of the transmitter is connected to the axis of the wind vane and that of the receiver carries the indicating needle of the wind-direction indicator.

The a.c. magnet field created by the transmitter's rotor induces voltages in the three stator windings of the transmitter. The magnitude of the induced voltage in any one of the windings depends on the disposition between the rotor and the winding itself. The resulting currents are passed by the three-lead cable to the stator of the receiver, there creating a resultant magnetic field with a polarity corresponding to the position of the transmitter's rotor. The interaction between the receiver's rotor magnetic field and the receiver's stator magnetic field brings the receiver's rotor to exactly the same position as that of the transmitter. Thus, the two rotors follow each other's motion synchronously. Depending on the mechanical load in the receiver a position difference error may appear, but with negligible friction in the indicator bearings this is unlikely. A much more significant error will result from an interchange of the cable leads.

The standard exposure of the wind vane, as well as the anemometer is internationally agreed to be over open, level terrain, at a height of 10 metres. Open terrain is defined as an area where the horizontal distance between the instrument and an obstacle is at least ten times the height of the obstacle above the ground.

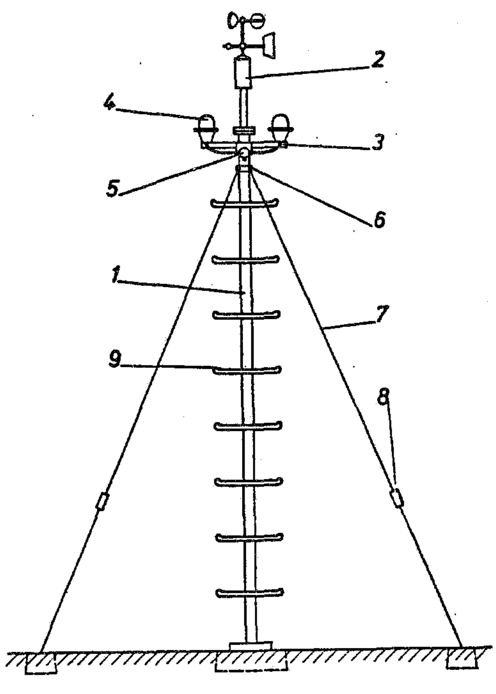


Figure 57 - Anemometer mast

At a meteorological station the wind-measuring instrument is usually installed at the top of a mast, so that the anemometer cups are 10 metres above ground-level (Figure 57). 10 metres is the standard height for operational wind measurements but, for special purposes, instruments may be installed at any suitable place and height above the ground, provided the necessary precautions are taken to ensure representative wind data.

The tubular mast (Figure 57) carrying the sensor head (2) should be provided with steps (9) in order to make the instrument accessible for maintenance. Red warning lights (4) may be installed immediately beneath the sensor head. All cables used (including power cables (3)) must be of a weather-proof type. The mast is provided with a concrete foundation and is additionally supported by guy-wires (7). The guy-wires are anchored in the concrete foundation and their tension is adjusted by wire-tension screws (8). Usually four wires are anchored at the corners of a square on the ground.

Sources of error are:

- Underdamping of the wind vane (less than 0.3);
- Axis of the wind vane not vertical;
- Centre of gravity of the vane not coincident with its pivot axis (vane nose-heavy or tail-heavy);
- Excessive mechanical friction in the vane bearings;
- Signal converter not properly adjusted to the vane's axis and north reference.

The wind vane and its sub-assembly hardly need any testing even after major maintenance. A careful examination of the instrument in respect of the possible sources of error should suffice.

5.2.2 The pressure-plate anemometer

The pressure-plate anemometer (Figure 58) is also known as the Wild anemometer, after its designer. It is a rugged but rather unsophisticated instrument for wind direction and speed measurement. In essence it is a metal plate (5), capable of swinging like a pendulum about a horizontal axis (8). The axis itself and the scale (7) of the instrument are fastened to the wind vane (4), thus the metal plate is always exposed with its broadside normal to the wind flow.

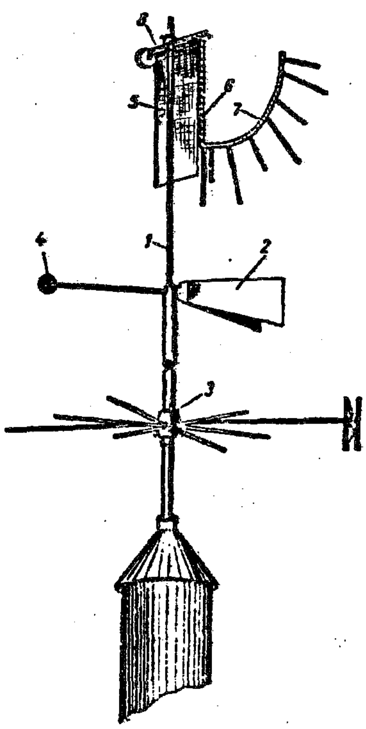


Figure 58 - Pressure-plate anemometer

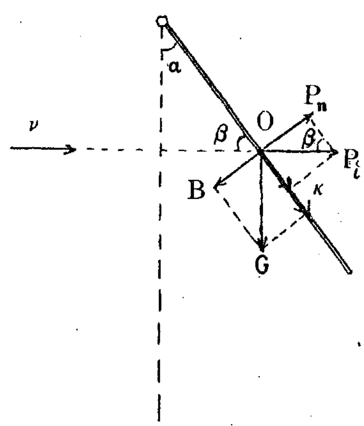


Figure 59 - Pressure-plate vector diagram

An analytical expression for the response of the pressure-plate to the wind speed can be obtained by referring to Figure 59.

The force exerted by the wind on a normally exposed flat plate of surface area S can be represented as follows:

$$P_o = C.\rho.S.v^2 \qquad (1)$$

where:

C = drag-coefficient ($C \simeq 0.64$);

ρ = density of the air;

v = wind speed.

From the parallelogram of forces (Figure 59), which can be imagined as being applied to the "centre of pressure", O, of the pressure-plate, equation (1) gives:

$$P_\iota = C.\rho.S'.v^2 = C.\rho.v^2.S \cos a \qquad (2)$$

where:

$S' = S \cos a$ is the effective area of the plate.

The "normal" lifting component, P_n, is expressed as a cosine function of P_ι:

$$P_n = P_\iota \cos a = C.\rho.S.v^2 \cos^2 a \qquad (3)$$

The counteracting force is a gravitational one:

$$B = G \sin a \qquad (4)$$

where:

G = the force of gravity.

In an equilibrium state with the metal plate deflected by the wind through an angle, a:

$$B = P_n \qquad (5)$$

Substituting (3) and (4) in (5) gives:

$$G = \frac{C.\rho.S.v^2 \cos^2 a}{\sin a} \qquad (6)$$

and finally:

$$v = \frac{G}{C.\rho} \frac{\tan a}{\cos a} \qquad (7)$$

It is evident from equation (7) that the pressure-plate response to the wind is not a linear function of the wind speed and depends on the air density. The air density varies with the atmospheric pressure (height above mean sea-level) and air temperature. This necessitates correction of the readings of the instrument according to the relationship:

$$v_{cor} = v.b \qquad (8)$$

where:

b = a correction coefficient according to the table:

$t^{o}C$ / P (hPa)	1 000	800	600
-20	0.94	1.10	1.27
0	0.98	1.14	1.33
+20	1.00	1.18	1.37

The pressure-plate sensor is of inferior accuracy; both wind vane and plate are second-order measuring systems and tend to oscillate. The original Wild anemometer has no damping and it takes a certain experience to make correct measurements.

Sources of error are:

- Tendency to oscillate around the true value of the measured quantity;
- Excess friction in the bearings;
- Low accuracy scale.

The exposure and testing of the instrument are as in the preceding paragraph.

5.2.3 The rotation sensor: cup-wheel - propellor. Signal converters for rotation sensors - electrical contact breaker - light-chopper - direct-current generator - alternating-current generator

The cup anemometer (Figure 60) is based on the use of the so-called cup wheel. Three or four aluminium or plastic cups mounted symmetrically about a vertical axis at the ends of the same number of arms protruding from the hub of the wheel. Because the force of the wind is greater on the concave side of the cup in comparison with the convex side, the cup wheel will rotate in the air stream. For any given cup anemometer there is a minimum wind speed which will set the cup wheel in motion, depending on the friction in the bearings of the wheel and the design parameters of the instrument.

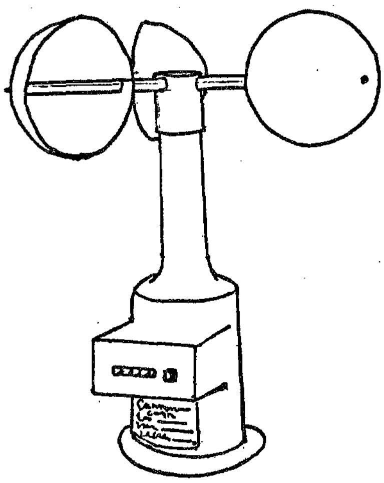


Figure 60 - Wind-path, cup-wheel anemometer

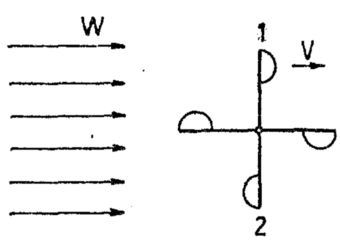


Figure 61 - Cup-wheel diagram of forces

The rate of rotation does not depend on the wind direction nor to any appreciable degree on the density of the air. Robinson introduced the cup-wheel anemometer based on the following theory:

The amount of forces responsible for the rotation, as mentioned above, is due to the difference in value of the aerodynamic drag-coefficients C_1 and C_2 of a cup when exposed to the wind with its concave or convex side. With a four-cup wheel (Figure 61), the following relationship holds:

$$F_1 = C_1 . \rho . S . (w - v)^2 \tag{1}$$

$$F_2 = C_2 . \rho . S . (w - v)^2 \tag{2}$$

where:

- F_1 = force acting on cup No. 1;
- F_2 = force acting on cup No. 2;
- w = wind speed;
- v = rotation speed of cup wheel;
- ρ = density of air;
- S = cross-section of area of cup;
- C_1 = drag-coefficient, concave side;
- C_2 = drag-coefficient, convex side.

If at a given wind speed, w, a rotation speed, v, is attained ($F_1 = F_2$) equation (1) and (2) render:

$$C_1 (w - v)^2 = C_2 (w + v)^2 \tag{3}$$

$$C_1/C_2 = (w + v)/(w - v) \tag{4}$$

Measured experimentally with an accuracy of 2 per cent, the ratio of C_1/C_2 substituted in equation (4) gives:

$$w/v = 3 \tag{5}$$

Experiments in different wind-speed conditions with anemometers of different design parameters proved that the ratio w/v varies slightly. A relationship valid over the whole meteorological range of wind speeds is:

$$w = w_o + Av + Bv^2 \ (\mathrm{m\ s^{-1}})$$

where:

- w_o = minimum wind speed capable of setting the wheel in motion;
- v = turning speed of cup wheel;
- A = coefficient depending on the cup-wheel design;
- B = coefficient depending on design: $B = 0,0001.A$.

In a steady wind the cup wheel performs well from almost 0.5 m s^{-1} up to 60 m s^{-1}. In gusty winds, however, it tends to read a higher average wind speed than the actual one. This is because the cup wheel, having inertia, accelerates more rapidly with an increasing wind speed than it decelerates with decreasing wind speed.

The behaviour of the cup wheel in a gusty wind has been extensively investigated. Schrenk has suggested the following dimensionless parameter, K, concerning the overestimation of the wind speed by the cup wheel sensor:

$$K = \frac{0.55\ \rho . R^2 . r^2 . T . v}{I}$$

where:

T = period of the variation of the wind speed;

v = mean wind speed;

ρ = density of the air;

R = radius of the circle described by the centre of the cups;

r = radius of the cups;

I = moment of inertia of the rotating parts of the cup wheel.

The overestimation of the wind speed is proportional to 1/K.

It is evident from the above relationship how strongly the overestimation of the average speed of the wind depends on the design parameters of the cup wheel as well as on the wind parameters.

Experimentally, it has been established that the response of the cup wheel to a sudden change of the wind speed deviates from the exponential one. Generally speaking, the speed of response is faster at higher wind speeds.

Sources of error are:

(a) Gradual increase of friction in the bearings with time;

(b) Change of aerodynamic properties and weight because of icing;

(c) Damage to cup wheel.

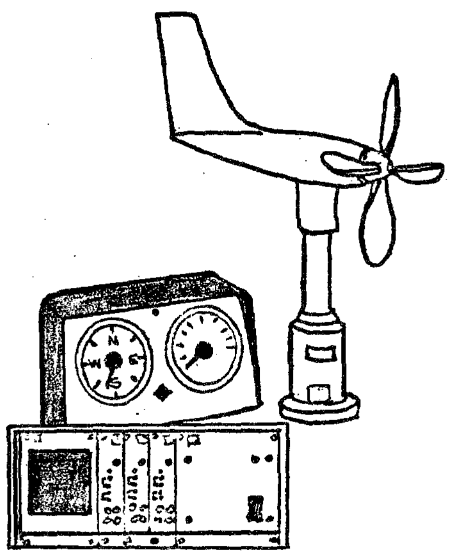


Figure 62 - Propeller anemometer

A different rotation sensor for wind speed is the propeller (Figure 62). The theory of the propeller has been thoroughly developed in connexion with aircraft flight. With its specific construction, being actually a very narrow segment of a "screw", the aeroplane propeller "screws" itself into the air and its rotation pulls the aeroplane. The function of the propeller could be inverted with the air moving with respect to the propeller blades. The air pressure on the blades would make the propeller rotate with a turning speed which is a function of the speed of the wind. In order to perform properly as a wind-speed sensor the propeller's axis must be parallel to the wind vector.

The propeller wind-speed sensor consists of a hub to which two or more blades are fastened symmetrically and set at an angle to the wind known as the angle of attack (Figure 63).

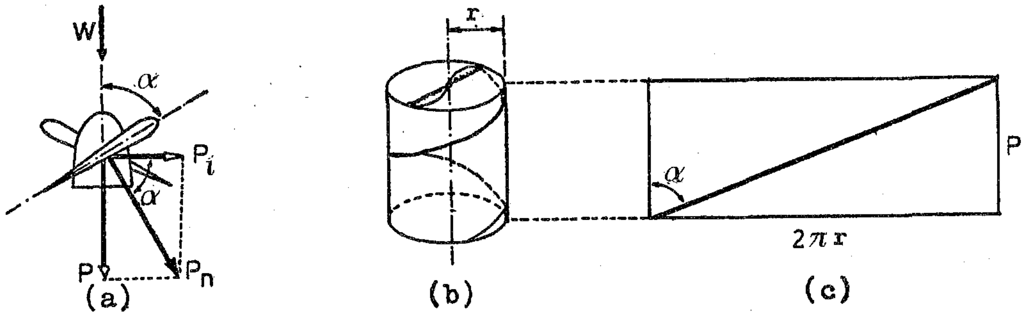


Figure 63 - The propeller-sensor parameters

The diagram of the forces acting on the propeller blade is given in Figure 63 (a), where:

w = the wind vector direction;

P = axial force component (neutralized by the reaction of the bearing);

P_t = tangential component (causing the propeller to turn);

P_n = the force of the wind acting normally on the blade (actually P_n is deflected by a small angle α from its "normal" position in a direction away from P_t).

The helical path of the propeller is presented in Figure 63 (b), and in Figure 63 (c) the same helical path is presented "unfolded". The following relationships hold:

$2\ \pi\ r/t = v$ (the turning speed of the propeller);

$P/t = w$ (the wind speed; t = time);

$v/w = \mathrm{tg}\,\alpha.$ (1)

Actually, the relationship showing the response of the propeller to the wind speed should take into account the design peculiarities of the sensor through a coefficient, A, very nearly equal to 1:

$$w = \frac{v}{A.\mathrm{tg}\,\alpha} = B.v \qquad (2)$$

where:

$B = 1/A.\mathrm{tg}\,\alpha$

The linear relationship between w and v is an advantage.

If A = 1 and $\alpha = 45^{\circ}$, w = v, compared to w = 3v by the cup-wheel sensor!

Actually, the optimum angle of attack of the blades has been found to be about 40°.

A deviation of the propeller axis from the direction of the wind-vector direction within $\pm 18^{\circ}$ causes a measurement error of wind speed of as much as 2 per cent. It should be mentioned that air-density variations with the elevation of the measurement site affects the measurement accuracy of the propeller sensor by less than one per cent.

Due to the relatively high turning speed of the propeller, its application is usually limited to the 0 - 40 m s^{-1} wind-speed range.

Like the cup wheel, the propeller sensor also overestimates the average speed of a gusty wind, but to a lesser degree.

The angle of attack of precision propeller sensors is not a constant, but decreases from the hub towards the tip of the blade in accordance with the increasing turning speed of the blade section.

Sources of error are:

(a) Gradual increase of friction in the bearings with time;

(b) Deviations of the propeller axis from the wind-vector direction by more than 20°.

One frequently-used signal convertor suitable for remote indication of the wind speed through the use of rotation sensors is the electrical contact-breaker. This may be a purely mechanical worm-and-cog-wheel cam-controlled contact-breaker or a permanent magnet reed-relay device. In either case the frequency of the train of the electrical pulses obtained, which is proportional to the wind speed, is measured by a frequency meter (Figure 64). (See also Part 3.) The train of pulses having a frequency (repetition), f, is converted by the frequency-meter into an average current through the indicator (a microammeter) according to the relationship:

$$I = f.C.U$$

where:

I = d.c. average current;

C = capacitance of the capacitor, c;

U = amplitude of the voltage pulse at the collector of the transistor, T_1 (assuming the transistor is brought to saturation during the ON stage).

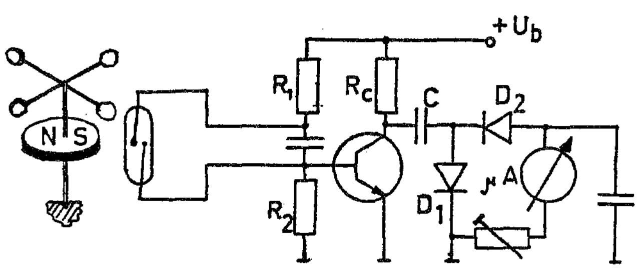


Figure 64 - Frequency-meter-based wind-speed indicator

The electrical pulses fed into the input of the circuit in Figure 64 are amplified by the transistor, T_1. The régime of operation of T_1 is chosen in such a way that its collector current swings with the closing and opening of the reed-relay between the two extremes: saturation and non-conductance. This results in amplified pulses of magnitude almost equal to the magnitude of U_b.

During the non-conducting phase, the capacitor, c, is charged to a voltage, U_b, through the diode, D_1. During the conducting phase of the transistor, T_1, the capacitor is discharged through the diode, D_2, and the microammeter. The meter filter capacitor, c_f, serves to smooth the pulsating direct current.

The current through the reed-relay is about one milliamp and there is virtually no voltage drop along the cable, whose length presents no problems (within reasonable limits) for the operation of the circuit. Armoured telephone cable can be used with its shield earthed.

A disadvantage of the signal converter is the presence of an additional mechanical load on the sensor, owing to the magnetically controlled switching of the reed-relay. The weak magnetic field needed contributes to an increase in the minimum threshold value of the wind speed capable of setting the cup wheel in motion. Another disadvantage is that the contacts wear out.

A similar but more sophisticated signal converter for rotational sensors is one converting the revolutions of the instrument's axis into a pulse train of voltage pulses through the use of an optical light-chopper (Figure 65).

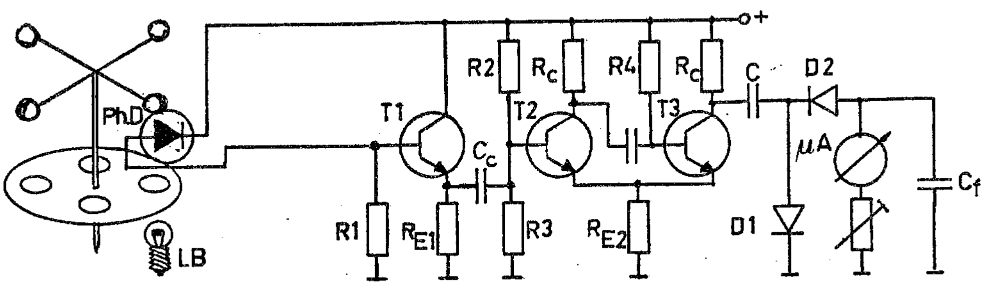


Figure 65 - Optical light-chopper

The <u>light-chopper converter</u> consists of a light source LB (light bulb or LED), a perforated disk fixed to the axis of the rotation sensor and a photodiode, PhD. The resistance of the reverse-biased photodiode falls in proportion to the illumination by the light source through a hole in the disk. When the diode is illuminated, the voltage at the transistor input is changed in such a way as to make it conducting and a voltage pulse appears at the emitter resistance, R_{E1}, of T_1.

The pulses thus obtained due to the rotation of the disk are then applied through the coupling capacitor, C_c, to the input of the one-shot multivibrator (see Part III) based on the transistors T_2 and T_3. At the output of the multivibrator, corresponding pulses are obtained having fixed width and amplitude. The pulse shaper, the multivibrator, adds to the precision of the frequency measurement.

The train of pulses of frequency, f, are further converted into direct current and measured by a microammeter, as in the previous circuit.

A relationship similar to the one already discussed links the pulse frequency to the average current, I, through the indicator:

$$I = f.C(U_1 - U_2) \qquad (1)$$

where:

f = pulse repetition frequency;

C = capacitance of the "diode-pump" (D_1, D_2) coupling capacitor;

U_1 = collector voltage of T_2, non-conducting;

U_2 = collector voltage of T_2, saturated.

In the case of a cup-wheel rotation sensor, the wind speed may be expressed by:

$$w = A.f \qquad (2)$$

where:

A = constant of the pulse signal converter;

f = pulse frequency at the output of the signal converter.

Hence:

$$w = \frac{A.I}{C(U_1 - U_2)} = B.I \qquad (3)$$

where:

$B = A/(C.U_1 - C.U_2)$.

Both signal converters are suitable for the remote indication of wind speed and the production of analogue signals at their respective outputs.

The light-chopper transducer is especially suitable for use with high-accuracy, low-minimum wind-speed threshold rotation sensors, having low power consumption.

<u>The direct-current wind-speed signal converter</u> (the d.c. generator principle is considered in more detail in Part III) consists of three main parts: a stator, S (in the case of the wind-speed signal converter, this is a permanent magnet), a rotor, R, and a collector-commutator device, CC. The stator provides a magnetic flux, Φ, the rotor, fixed to the rotation sensor's axis, turns at N revolutions per unit time and a voltage is induced in its winding. The collector-commutator device rectifies the alternating voltage produced at the rotor winding terminals.

The d.c. voltage appearing at the brushes of the generator is measured by a high input resistance voltmeter, whose scale is graduated in wind-speed units following the relationship:

$$U = k.\Phi.N; \qquad (1)$$

$$N = D.w; \qquad (2)$$

$$w = \frac{U}{k.\Phi.D} = U.\text{const.} \qquad (3)$$

where:

k = a constant depending on the design parameters of the generator;

Φ = the d.c. generator's stator magnetic flux;

N = revolutions per unit time of the rotor;

D = a proportionality constant accounting for the sensor's features;

w = wind speed.

The d.c. generator signal converter for rotation sensors is a rugged device and has a linear output. Its main deficiency is that the generator creates a torque which, added to the friction in the sensor's bearings, raises the wind-speed theshold of the instrument.

For the purpose of remote sensing of wind speed a special kind of a.c. generator is used - the brushless generator (Figure 66).

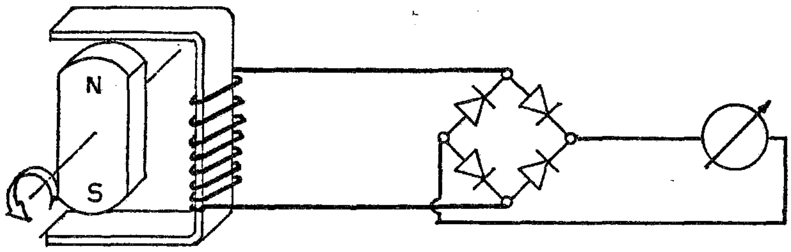


Figure 66 - Circuit of an a.c. generator wind-speed transducer

The voltage output of the a.c. generator is also a linear function of the speed of rotation of its rotor - a permanent magnet:

$$w = U.\text{const.}$$

With a microammeter as an indicator the use of a rectifier is necessary.

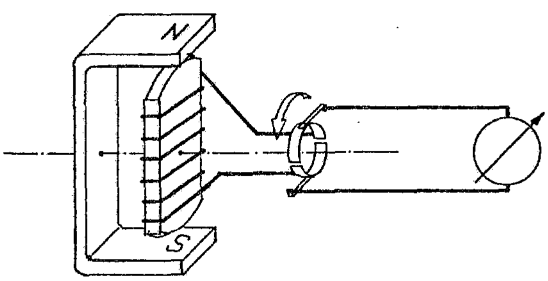


Figure 67 - Circuit of a d.c. transducer

The wind-speed signal converter based on the a.c. generator is generally more reliable than the d.c. device. Another advantage over the d.c. generator is that the rotating permanent magnet induces the a.c. voltage in the stationary stator winding thus making collector and brushes unnecessary.

5.2.4 The Pitot tube/Krell's micromanometer arrangement

The measurement of wind speed by use of a Pitot tube (Figure 68) and Krell's micromanometer (Figure 69) is based on Bernoulli's law.

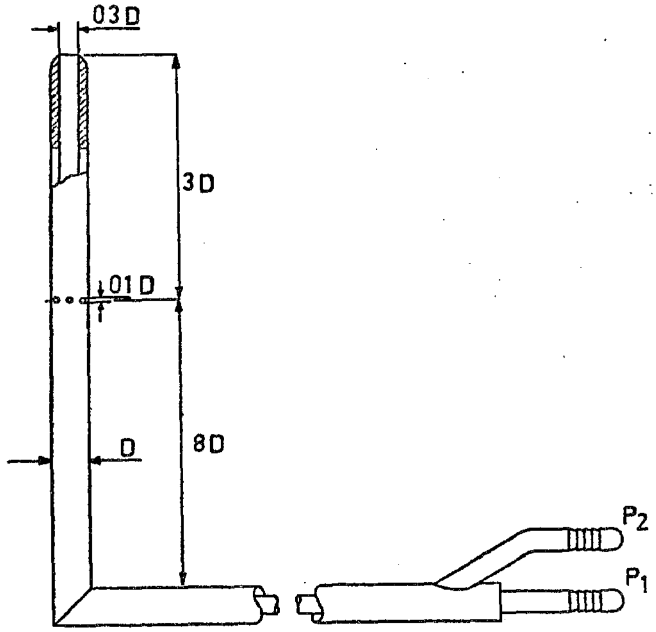


Figure 68 - Pitot static tube

The total pressure in a moving fluid can be represented by:

$$P = P_{st} + P_d \tag{1}$$

where:

P_{st} = static pressure;
$P_d = \rho . w^2/2$ = dynamic pressure;
w = velocity of the moving fluid.

Applying Bernoulli's law for the moving airstream, using the simple manometer pictured in Figure 70, the following expressions for the total pressure at the manometer openings (1) and (2) are obtained:

$$P_1 = P_{st} + \rho . w^2/2 \tag{2}$$

$$P_2 = P_{st} - k . \rho . w^2/2 \tag{3}$$

where:

k = a coefficient.

Subtracting (3) from (2) gives:

$$P_1 - P_2 = h = (w^2/2)(1 + k) \tag{4}$$

Therefore:

$$w = \sqrt{\frac{2.h}{(1 + k)}} \quad \mathrm{m\ s^{-1}} \tag{5}$$

for h in mm of water column and P_1, P_2 in kg m^{-2}.

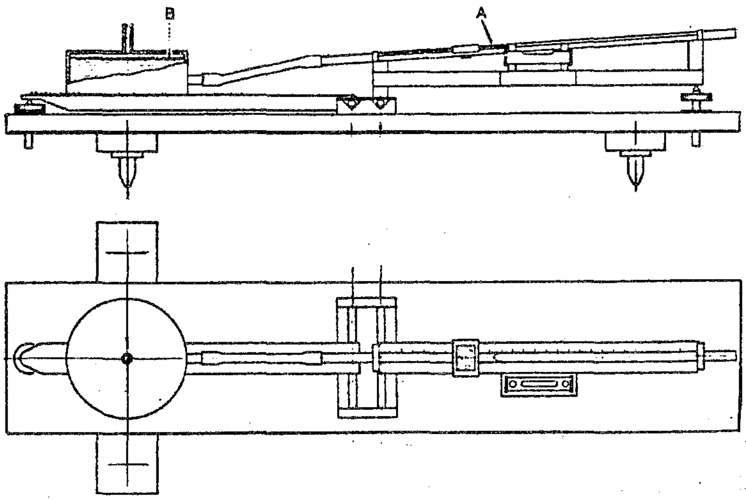


Figure 69 - Krell micromanometer, wind-speed indicator

The airstream speed can be suitably measured with the Pitot tube/Krell manometer arrangement using the relationship in equation (5).

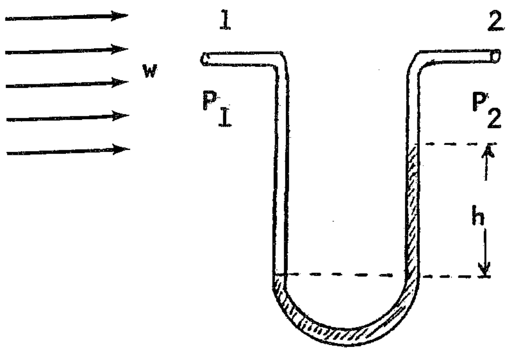


Figure 70 - U-type manometer

Comparing Figure 68 and Figure 70, it becomes apparent that with the original Pitot tube the legs (1) and (2) are made of coaxial tube, (2) having the larger diameter and being the outer tube of the Pitot tube sensor. The opening (2) in Figure 70 is replaced by a number of small holes of 0.1 D, where D is the diameter of the Pitot tube, situated at a distance of about 3 D from the opening (1).

The pressures P_1 and P_2 are taken from the opposite ends of the inner and outer tubes of the sensor through connecting plastic hoses.

The Krell manometer consists of a reservoir B filled with the manometric liquid (water: specific gravity = 1 ; alcohol: specific gravity = 0.8; or mercury: specific gravity = 13.56) and connected to it a manometric tube, A, inclined at an angle, a.

Depending on the angle, a, the specific gravity of the manometric fluid, c, and the read-out on the scale of the manometric tube, l (in mm), the pressure difference $P_1 - P_2 = h$ (mm water) can be obtained from the relationship:

$$h_{(mm\ water)} = l.c.\sin a$$

The pressure values can be obtained for each of the manometric fluids indicated in the table:

Pressure in mm water column

sin a	mm water pressure per scale division		
	water	alcohol	mercury
1:1	1.0	0.8	13.56
1:2	0.5	0.4	6.78
1:5	0.2	0.16	2.71
1:10	0.1	0.08	1.36
1:25	0.04	0.032	0.54

Before use, the Krell manometer should be levelled carefully. A spirit-level is fastened to the base plate of the instrument. Three levelling screws with knurled heads are used to level the base-plate.

The Pitot tube is exposed to the wind, its axis parallel to the wind direction. Small deviations from the wind direction may be tolerated. The Pitot tube outlets are connected to the Krell manometer by plastic hoses. Sharp bends in the hoses should be avoided.

While the sensor can be used for outdoor measurements, its true application is for indoor laboratory measurements. The instrument is an accurate one used as a standard instrument in the wind-tunnel calibration of anemometers.

Air density plays an important rôle in the measurement of wind speed. Pressure, temperature and humidity values are necessary for the correction of the air density.

Sources of error are:

- Large deviation of the Pitot-tube direction from the wind direction;
- Erroneous values of air density;
- Krell manometer not levelled properly;
- Specific gravity of manometric liquid inaccurately measured;
- Obstructions in the sensor's ducts (small insects, dirt).

With all the necessary conditions of the measurement observed, the Pitot tube should give accurate results.

The instrument itself is used as a standard instrument.

5.2.5 Thermoanemometers

One of the simplest designs of thermoanemometer is the katathermometer (Figure 71). The katathermometer looks like an ordinary thermometer, apart from two bulbous expansions of the capillary - the lower, the actual reservoir and the higher, an excess-liquid reservoir.

Figure 71 - Katathermometer wind-speed sensor

The range of the thermometer is rather narrow: 35^{o} - 38^{o}. The air speed is measured by the katathermometer through its cooling rate: $H = F/t$,

where:

F = heat lost per unit area (cm^2) of the thermometer's reservoir;

t = time for the thermometer to cool from 38^{o} to 35^{o}C.

In order to measure the wind speed (usually in the cm s^{-1} range), the katathermometer is heated above 38^{o}, the excess liquid filling the upper reservoir and then left to cool. The time taken for the temperature to drop from 38^{o} to 35^{o} is measured by a stop-watch. The wind speed is obtained from one of the semi-empirical relationships, $w = f(H)$, which are given in the certificate of the thermometer. One such relationship, quoted in manuals on meteorological instruments, is:

$$B^2 . w = \left(\frac{F}{(36.5 - t^{o}).t - A}\right)^2$$

where:

t^{o} = air temperature;

A, B are experimental constants varying slightly for different instruments;

w = wind speed.

This method has the advantage in that it is possible to measure very low wind speeds, which is impossible using the conventional rotation sensors.

The principle of the electrical thermoanemometer - hot wire anemometer - is illustrated in Figure 72. It is based on the measurement of the cooling effect of the moving air on an electrically heated platinum wire. The temperature of the platinum wire is measured by a thermocouple thermometer, the heating current, I, and hence the electrical power converted into heat, being measured through the milliameter and controlled by the potentiometer, R. The electrical energy is supplied by a storage battery of voltage U.

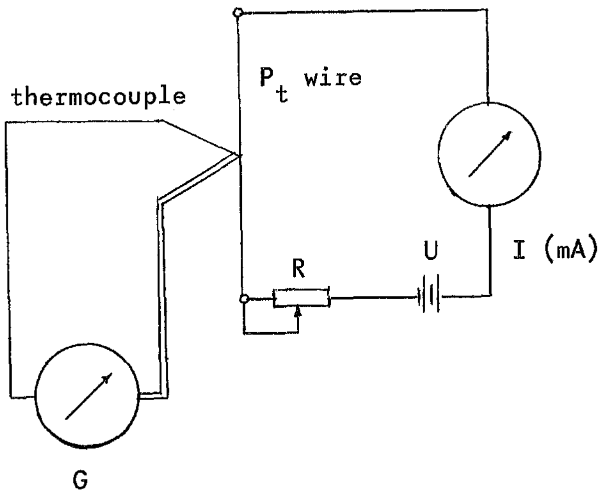


Figure 72 - Circuit of a thermoanemometer

The theory of the instrument is based on expressions for the convective heat exchange:

$$dQ/dt = aS(t^{o} - \Theta) \qquad (1)$$

and for the electrical power dissipated in the P_t wire:

$$dQ_e/dt = 0.86 I^2 R_p \qquad (2)$$

where:

Q = heat taken away from the platinum wire by convection (forced) in the airstream;

Q_e = heat dissipated by the electrical current in the platinum wire;

t = time;

a is a coefficient of convective heat exchange (a function of the airstream speed, w);

S = surface area of the platinum wire, subject to heat exchange;

t^{o} = temperature of the platinum wire;

Θ = ambient temperature;

I = current through the platinum wire in amperes;

R_p = the "hot" electrical resistance of the platinum wire in ohms.

In an explicit form the relationship governing the response of the electric thermoanemometer is:

$$\frac{Q_e}{t^o - \Theta} = K_o + K_1 . w^{-1/2}$$

where:

Ko, K = constants.

Instead of using a separate thermometer, the temperature of the platinum wire may be calculated at a constant source voltage from the voltage drop across R (the control resistor) and the current, I.

With the principle of the thermoanemometer shown in Figure 72, two approaches are possible:

(a) With a constant temperature difference ($t^o - \Theta$) to find the wind speed, w, as a function of the heating current: w = f(I);

(b) With a constant heating current to find the wind speed, w, as a function of the temperature difference: $w = f_i(t^o - \Theta)$.

Both approaches are easily realized by electronic control of either I or ($t^o - \Theta$) and contemporary electronic thermoanemometers using miniature probes of micrometre-gauge wire are capable of measuring wind speeds in the range from cm s^{-1} to around 20 m s^{-1}.

Exposure of the probe of the instrument should guarantee the efficient heat exchange assumed with the particular design. With a relatively long, stretched platinum wire, the proper conditions for optimum heat exchange between the wire and the airstream is with the wire orientated to be normal to the airstream.

Sources of error are:

- Deviation from the exposure rules;
- Unaccounted fluctuations in the supply voltage.

Thermoanemometers of the kind described above should be tested periodically. The electrical thermometer and the current indicator should be tested and calibrated. Also, the change of internal resistance of the storage battery should be checked, especially if the resistance of the wire is used to measure its temperature.

5.2.6 Anemometers measuring run-of-wind

Rotation-sensor anemometers, based on wind-speed-to-frequency conversion can be made to indicate run-of-wind instead of wind speed. Usually, the indicator is a digital counter of a mechanical type, actuated by a suitable conversion gear between the sensor axis and the counter spindle.

5.2.7 Anemographs - the pressure-tube type and the electrical ring-potentiometer type

The pressure-tube anemograph uses the principle of measurement of wind speed already discussed in connexion with the Pitot tube. The instrument consists of three main units (Figure 73):

(a) Pressure tube and vane assembly (1, 2, 3);

(b) Pressure and vane position transmitting assembly (4, 5, 5, 6, 7, 13);

(c) Wind speed and direction recording assembly (8, 9, 10, 11, 12, 14).

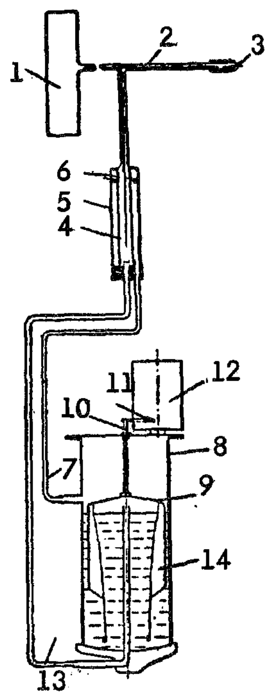


Figure 73 - Principle of pressure-tube anemograph

The pressure tube is firmly fixed to the wind vane, thus its pressure inlet (3) faces directly into the wind. Pressure and suction are transmitted through two pipes (7, 13) to the recording assembly.

The pressure difference between the static and dynamic pressure, p, produced at the outlets of the pressure tube is proportional to the square of the wind speed:

$$\Delta p = (1/2)K\rho w^2 = 0.093w^2 \text{ mm water column}$$

for w in m s^{-1} and air of standard density ρ = 1.226 kg m^{-2}; K is a constant depending on the design of the instrument.

There are two alternative versions of the pressure and vane-position transmission assembly depending on whether the instrument is direct-recording or remote-recording:

(a) With the direct-recording version (recording assembly installed immediately below the sensor head in a building from the roof of which the mast protrudes), the vane position is transmitted to the recording assembly by means of a metal rod;

(b) With the remote-recording version the vane position is transmitted to the recording assembly by means of a selsyn device.

Correspondingly, there are two versions of the recording assembly. In both, the recording of wind speed and direction is made on one and the same chart wound on a clock-driven drum (12) of height 219 mm and diameter 127 mm. The time scale of the record is 15 mm h^{-1}.

The wind-direction part of the chart consists of a vertical scale in degrees from north through west, south and east to north. Two pens are used for direction recording. At any one time, one of the pens rests on the top or bottom north line while the other is active. If the active pen, because of veering or backing of the wind to north from a mid-scale position , reaches the resting pen's baseline, the former immediately returns to its resting north line while the latter takes over the recording. This is achieved by means of a double helix on the wind-vane spindle which controls the movement of the pens. The pens, guided by the helix grooves, are balanced with counterweights so that the upper pen tends to rise while the lower one tends to fall, each to its respective baseline.

The connexion between the cylinder shaft and the spindle of the vane is flexible, ensuring smooth movement. An additional direction dial is fixed to the cylinder shaft for direct read-out of the wind direction.

With the remote-recording instrument, the cylinder shaft is coupled electrically to the wind vane by means of a selsyn system. The rest of the recording gear is the same.

The wind-speed recording is made on the upper half of the chart by a specially designed float manometer which gives a deflection proportional to $\sqrt{\Delta p}$, thus linearizing the response of the pressure tube.

The bell-shaped float (9) is placed mouth-downwards in a cylindrical tank (8) containing distilled water. The pressure-tube front orifice is connected to the space inside the float above the water level through the transmitting pipes and a vertically mounted pipe segment inside the tank. The suction tube (7) is connected to the space outside the float above the water surface. The outer surface of the float is cylindrical but the inner surface is specially shaped to give the required scale.

The movement of the float is transmitted to the recording pen by a rod attached to the upper part of the float. The rod's upper end carries a cup containing lead shot. The zero position of the pen is adjusted by the addition or removal of lead shot.

The theory of the instrument is given by E. Gold (Wind in Britain, Quart. Journal, 62, Royal Met. Soc., London, 1936).

For the exposure of the instrument's sensor (pressure tube and vane assembly), a 10-metre mast or lattice tower is used. Conditions for siting the mast have already been discussed in a previous section.

Sources of error are:

(a) Obstruction in the inlet of the pressure tube (caused by icing, etc.);

(b) Water block at the bottom of the pressure-tube pipe (caused by rain, etc.);

(c) Leaks in the pipes or the tank;

(d) Changes in air density, ρ :

$$w = w_i \sqrt{\frac{\rho_o}{\rho}}$$

where:

w = true value of the wind speed;

w_i = the indicated value of the wind speed;

ρ_o = 1.226 g m^{-3} - standard air density;

ρ = $\frac{P}{RT}$, actual air density;

P = atmospheric pressure;

R = gas constant per gram of air;

T = absolute temperature;

(e) Change in water level in the tank;

(f) Excessive friction in the wind-vane rotary joint;

(g) Faults in the selsyn shaft-angle transducer.

The electrical ring-potentiometer (three-tap potentiometer) anemograph is a recording version of the three-tap potentiometer wind vane already discussed (Figure 74).

The wind vane's (1) axis is connected to the axis of the potentiometer (2) which is fed by a mains rectifier at two diametrically-opposed points of the winding. Through the three sliding contacts, rings and brushes (4), (3) and the three-core cable, the three control voltages are fed into the windings of the recording mechamism (5).

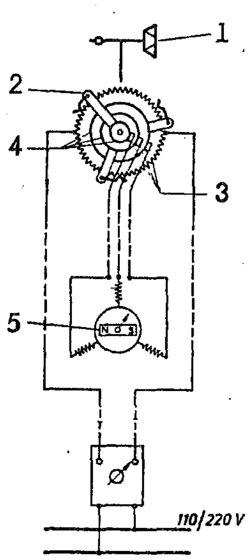


Figure 74 - Fuess, three-tap ring potentiometer system circuit

In Figure 75, the permanent magnet rotor (1) drives the recording pens of the device through the gear (2). The recording chart, wound on a clock-driven drum, is graduated in three different scales: wind-direction scale, graduated in degrees from north to east, south and west to north again (one-third of the chart); ten-minute average wind-speed scale graduated in knots; and the instantaneous wind-speed scale also graduated in knots.

The recording is made by passing an electric current with the help of sliding contacts (Figure 75) (3), (4), through the specially made electrosensitive paper. The pointed tips of the fine wire pens make a thin trace at the point of contact with the electrosensitive paper. There are six such pens fixed to the recording-gear axis. The pens are arranged so that as the wind vane passes through the north point, one pen leaves one edge of the chart as another pen starts recording at the other edge.

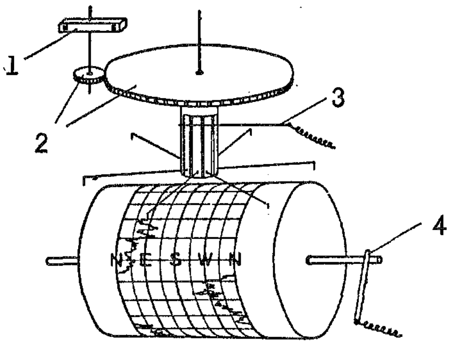
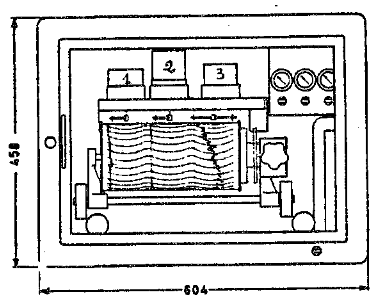


Figure 75 - Fuess, wind-direction recording gear

Because of the favourable transmitting ratio of the recording gear, the friction of the pen on the paper does not affect the accuracy of the wind-direction recording. A general view of the recorder with the instantaneous speed-recording device (1), average speed-recording device (2) and the wind-direction recording device (3) is shown in Figure 76.

Figure 76 - Wind-speed and -direction recording assembly



The signal converter of the cup-wheel wind-speed sensor is an a.c. generator and the recording mechanism works on the voltmeter principle with the indicating needle being replaced by a recording pen.

The ten-minute average of the wind speed is obtained from the rotation of the cup-wheel sensor. An electrical contact is actuated by the cup wheel. The contact is closed after a fixed run-of-wind and the electrical impulse obtained by the closure of the contact actuates a modified clock step-motor which turns the recording pen through a small fixed angle. A time switch brings the recording pen back to its initial position after a ten-minute interval. Thus, the trace on the chart records successive ten-minute averages of the wind speed.

Wind speed and direction sensors of the anemograph are installed at the top of a ten-metre high mast as with the pressure-tube anemograph.

Although based on the same principle, the three-tap potentiometer anemograph differs in construction from the anemometer by way of its recording unit. In addition to the sources of error already discussed in connexion with the anemometer, mention should also be made of the inaccuracies of the recording of the wind direction arising from "painting" of the direction recorder. The phenomenon of "painting", i.e. the recording pen sweeping the scale in wide, oscillating movements, is a result of underdamping of the wind vane.

CHAPTER 6

MEASUREMENT OF PRECIPITATION

6.1 General - liquid and solid precipitation - units of measurement

The precipitation reaching the ground is either in a liquid form (rain, drizzle, etc.) or solid form (snow, hail, etc.). For synoptic meteorology it is important to measure the total amount of precipitation: the sum of the amounts of liquid, and the liquid equivalent of solid precipitation.

Over a time period the total amount of precipitation is expressed in millimetres as the depth of liquid water which would cover a horizontal portion of the Earth's surface if there was no water loss at all. An instrument used for point measurement of precipitation is called a precipitation gauge. Precipitation is a meteorological variable with large spatial and temporal variability. Areal estimation of precipitation through point measurements is affected by error due to this variability and to the averaging of the individual measurements over the area. The desired accuracy of point-precipitation measurements is about 2 per cent.

In some countries, precipitation depth is still measured in hundredths of inches of liquid water, one inch being equal to 25.4 mm.

Snowfall is also measured as the depth of the snow layer, the unit of measurement being the centimetre. Fresh snow one centimetre deep is assumed to be equivalent to about one millimetre of liquid water . The specific density of fresh snow may vary between 0.03 and 0.4. Snow is still measured in tenths of inches in some countries.

6.2 Principles of the point measurement of precipitation

The amount of precipitation reaching the ground over an area is calculated by averaging the measurements made at individual gauges spread over the area in question.

6.2.1 Non-recording precipitation gauges - daily raingauges of the unshielded and shielded types - totalizers - accessories

The precipitation gauge (Figure 77) is a metal cylindrical can, open at the top, the rigid rim of the opening defining a collecting area of 200 - 500 cm^2, depending on the type of instrument.

Inside the precipitation gauge, a funnel receives the precipitation, leading it into a narrow-necked glass or plastic vessel. This design is aimed at eliminating splash-in and splash-out of precipitation and at protecting the collected water from evaporation losses.

The effect of wind on the accuracy of the measurement with a precipitation gauge can be substantially diminished by the use of a metal shield (Figure 78). One specific type of inverted-cone iron-sheet shield is known as a Nipher shield, named after its designer.

Weekly and monthly precipitation gauges are of similar design, but have a larger collecting vessel and a stronger construction. They are used on sites where daily measurements are impracticable.

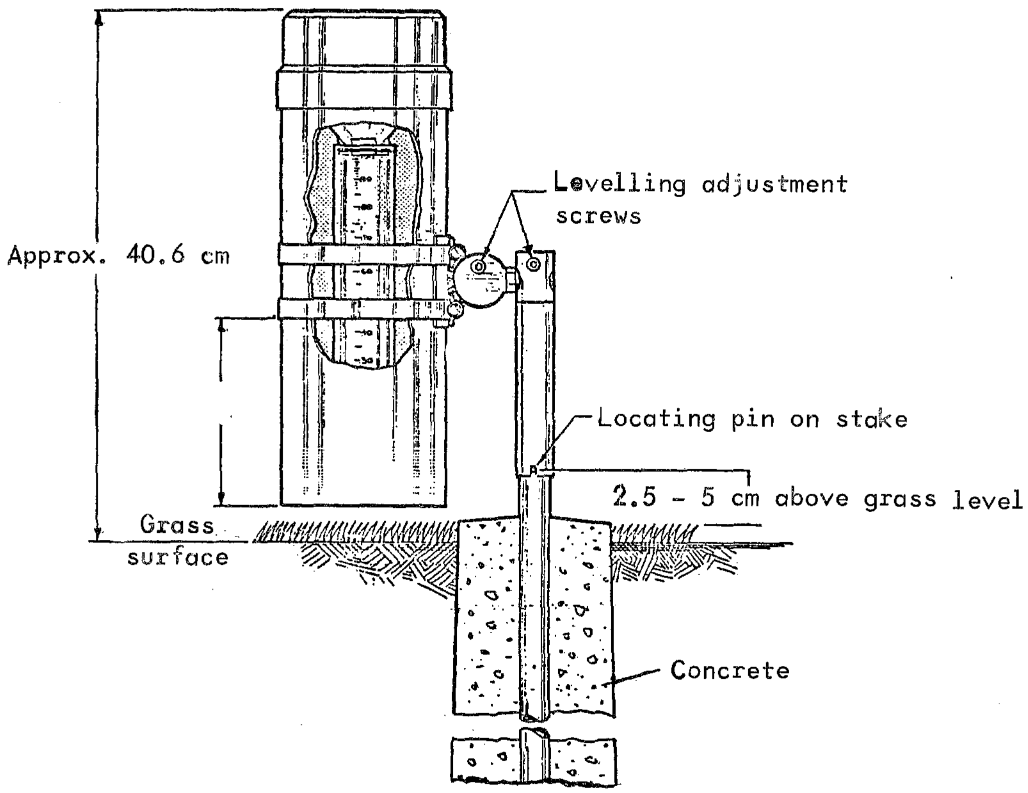


Figure 77 - Precipitation gauge, installation principle

Totalizers are used to measure precipitation on a seasonal basis at sometimes inaccessible places (mountain tops, valleys, etc.). They are similar to the normal precipitation gauge but for a much larger collecting vessel and the manner of exposure (mounted on a sturdy iron lattice tower of suitable height (in order to prevent snow-drifts from burying them)). Used in conditions of freezing temperatures and a season-long exposure they are charged with a known amount of antifreeze (most often 37.5% by weight calcium cloride and 62.5% water) and some evaporation-suppressing chemical (most often saturated, low-viscosity oil).

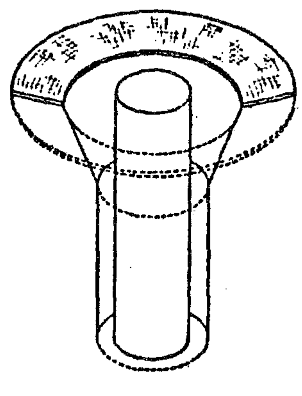


Figure 78 - Raingauge shield principle

Precipitation-gauge accessories are: measuring cylinder or dip-rod, used in measurement of the catch. The measuring cylinder is made of clear glass or plastic (Figure 79). Its graduation in millimetres of liquid precipitation is consistent with the size of the collecting area of the instrument. In any case, the graduation should permit a reading of 0.1 mm. The bottom of the measuring cylinder should be tapered in order to make possible the measurement of very small ("trace") quantities of precipitation (0.05 mm or less).

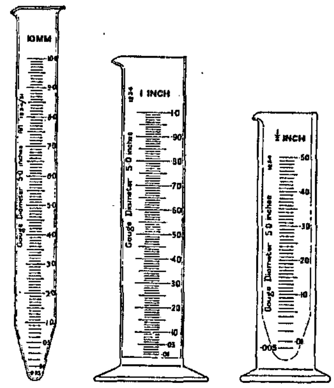


Figure 79 - Rain measures

Dip-rods, more suitable for use with weekly and monthly gauges, are usually made of cedar wood, which does not absorb water appreciably, or another suitable material. The graduation is in millimetres of precipitation, again consistent with the collecting area of the gauge. The graduation accuracy should not be less than ± 0.1 mm at any point on the scale. As measuring devices, dip-rods are inferior to measuring cylinders.

Snow can be measured using an ordinary precipitation gauge by adding a known amount of hot water to the solid precipitation collected. The melted snow and added water are measured together and the amount of the hot water subtracted from the total.

Measurements of solid precipitation with an ordinary gauge are error-prone.

Generally, there are three ways of installing the precipitation gauge: in the ground, with the collecting orifice flush with it (a special trench and anti-splash grid are used); on the ground; and elevated. The last installation version is used in countries with appreciable snowfall.

The exposure site of the instrument should be selected very carefully. The gauge should be exposed with the rim of the collector horizontal, over level ground and with surrounding objects not closer than four times their height. Local accelerations of the wind above the collecting orifice of the instrument should be avoided and, if possible, the wind speed should be reduced by a shelter of low vegetation, planted at a distance from the instrument. It should be remembered, however, that a shelter may be beneficial at one wind speed but deleterious at another.

Sources of error are:

(a) Inaccurately graduated measuring cylinders or dip-rods;

(b) Improper measuring practices: measuring cylinder held in a non-vertical position. Dip-rod dipped inclined to the water surface, etc.;

(c) Effect of wind on the precipitation catch;

(d) Effect of evaporation on the collected precipitation;

(e) Wetting of the gauge walls (error from wetting most pronounced with light rain).

Methods of correcting the errors connected with (c), (d), (e) are discussed at the end of this chapter.

6.2.2 Recording precipitation gauges - syphon (float) type - tipping-bucket - weighing-balance type

Recording precipitation gauges make use of the same arrangement for the collection of precipitation as the ordinary non-recording instruments.

Recording precipitation gauges may be classified into two major groups:

(a) Those which record the total amount of precipitation;

(b) Those which record precipitation intensity.

Both groups of instruments use ink-on-paper recording methods, the chart used usually being wound around a clock-driven drum with a daily or a weekly movement. Monthly recording instruments use strip-charts and relevant transport mechanisms having feed and take-up spools and an electric (battery-powered) drive.

Two types of precipitation recording gauges are based on the syphon water-discharge principle: natural syphon (Figure 80) and tilting syphon (Figure 82).

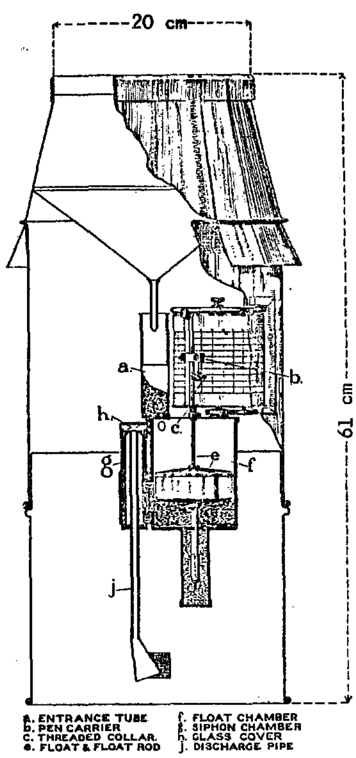


Figure 80 - Natural syphon rain-recorder

In the natural syphon recorder, the water collected in the funnel is led into a cylindrical chamber containing a light-weight metal-sheet float. The float is fastened to a rod and can move up and down without rotating about the axis of symmetry. As precipitation accumulates, the float is moved upwards by the water, transmitting its movement through the rod to a recording pen.

The collecting chamber has an outlet near its base which is connected to the instrument's discharge device. The discharge device consists of two coaxial tubes running parallel to the collecting chamber. The larger-bore tube's lower end is closed around the smaller one, whose upper end comes very close to the polished glass stopper of the larger tube. Because of the connexion between the collecting chamber and the large tube, the collected water reaches the same level in both of them. When it reaches the top of the smaller tube and flows over the bend, it causes a syphoning action to take place, discharging the accumulated precipitation from the collecting chamber. The float sinks to the bottom of the chamber and with it the pen returns to its initial position.

With continuous precipitation the float may make many excursions up and down, the rising movement following the rate of precipitation, the falling part being almost vertical, following the speed of discharge from the collecting chamber.

Rate of precipitation and total amount can be read from the record. A simpler version of the discharge tube differs from that shown in Figure 81 in that it consists of an upside-down U-shaped small-bore glass tube with one end connected to the collecting chamber. The water inside the chamber and the leg of the tube connected to it have the same level all the time. As soon as the water reaches the sharply bent part of the tube, a syphoning action is started, emptying the collecting chamber.

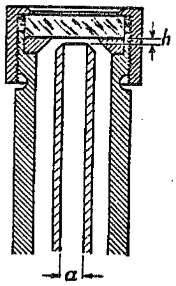


Figure 81 - Detail of draining tube of natural syphon

Different makes of recording precipitation instruments, based on the natural syphon principle of water discharge may have different chamber volumes. Some European-made instruments have a volume equivalent to 10 mm of precipitation.

The syphoning action must be fast enough to discharge the chamber without interruption. A small amount of precipitation entering the chamber during the discharge process is lost, this being the disadvantage of the design.

In the tilting-syphon type (Figure 82), as soon as the float reaches the upper part of the chamber and touches a trigger, the chamber which pivots on a knife edge, is tilted to the side of the syphon, thus accelerating the discharge process. The tilting chamber is balanced in such a way that, as soon as it is empty, it returns to its normal position re-engaging the trigger. Simultaneously with the tilt of the chamber the recording pen is lifted from the drum while the float returns to its initial position. The triggering occurs with the float reaching the 5-mm precipitation mark.

During installation of the instrument, care should be taken to level it properly.

For use in conditions of a moderate winter, a simple heating system consisting of light bulbs of 25 - 50 W is used. The heat dissipated by the light bulbs is enough to prevent the water freezing in the collecting vessel and syphon.

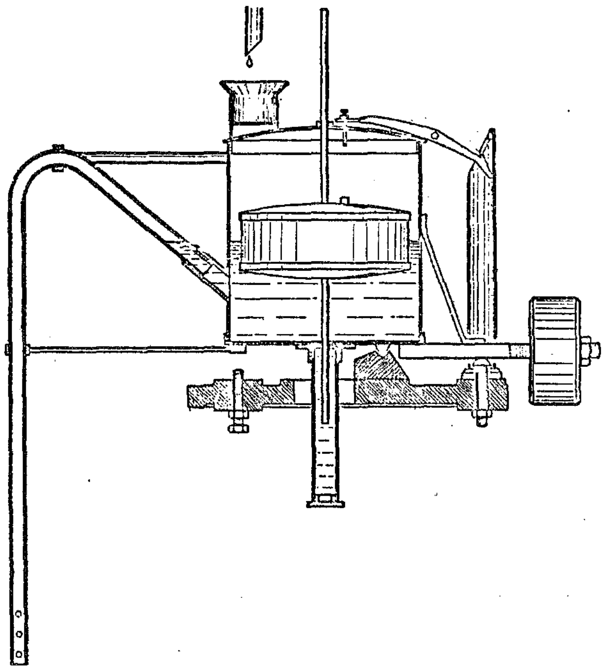


Figure 82 - Float chamber of tilting-syphon rain-recorder

The same rules are valid for the exposure of the instruments as for the ordinary raingauge. In addition, if a year-round operation of the instrument is envisaged, a nearby source of mains power will be required.

Sources of error are:

- Pen trace with zero precipitation is not horizontal;
- Syphoning action delayed due to obstruction or defect in discharge tube;
- Slightly punctured float and partly filled with water;
- Leaking collecting vessel;
- Misalignment of the triggering system of the chamber catch (tilting-syphon precipitation recorder).

A check of the collector area of an instrument after transportation or body repair is recommended. The check is performed through the use of a special disk having a slightly conical lateral surface and a thickness of about 15 mm. Three lines are engraved along the conical surface: one in the middle representing a circle of the standard collecting area (200 cm^2 or 500 cm^2); one below it representing a circle of slightly smaller diameter (one millimetre) than that of the standard circle; and one above the middle line, at slightly larger diameter (one millimetre) than that of the standard circle. With a good instrument, the middle line of the disk should coincide with the rim of the orifice of the precipitation gauge, the former being placed on top of it like a lid. An elliptical collecting area or one whose diameter is greater than the standard (or smaller) one by more than one millimetre would lead to an erroneous estimation of the precipitation amount.

The syphoning action is tested by pouring into the chamber a measured amount of water equal to the instrument's chamber capacity and observing the discharge of the water. With a tilting-syphon instrument, this would be a test for the triggering and chamber-release mechanism as well. Using the exact amount of water would enable the verification of the instrument's recording range.

The tipping-bucket precipitation recorder is an event-type sensor. As can be seen from the illustration (Figure 83) it is a twin metallic or plastic vessel of suitable shape, resting on a knife-edge support. The tube connected to the precipitation-collecting funnel is mounted above the tipping bucket, which has two stable positions while empty, either half of the bucket staying just below the outlet of the funnel. Because the centre of gravity of the full half of the bucket is outside the point of support, the bucket tips over as soon as it is loaded with a fixed amount of precipitation water, spilling the collected water and exposing the other empty half of the funnel outlet. As soon as this one is filled, it tips over to the other side. At each tipping motion a permanent magnet-actuated reed-relay switches an electrical circuit, producing an electrical impulse.

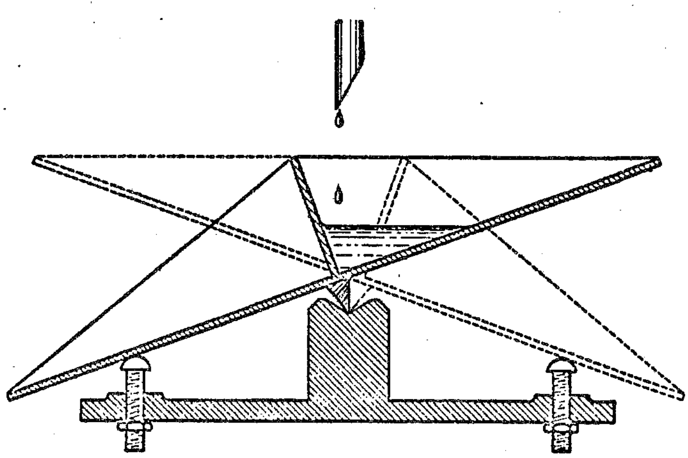


Figure 83 - Principle of tipping-bucket raingauge sensor

Each electric pulse obtained moves the pen, fastened to the axis of the ratchet and pawl recording relay, one step up across the recording chart (Figure 84). When the pen reaches the upper travelling limit, a release mechanism is triggered and the pen is brought down to its starting point on the baseline. Thus, the train of pulses coming from the reed relay with a frequency proportional to the rate of rainfall is recorded on the clock-driven chart as stepped lines with different inclination towards the baseline: the heavier the precipitation, the closer the trace to the vertical. As one step corresponds to a fixed amount of precipitation, the number of steps related to a fixed time interval read-out from the time axis on the chart, multiplied by the amount corresponding to one step gives the total amount of precipitation over that time interval. Usually (depending on the design), one step on the trace corresponds to 0.20 mm of precipitation (the volume of the bucket).

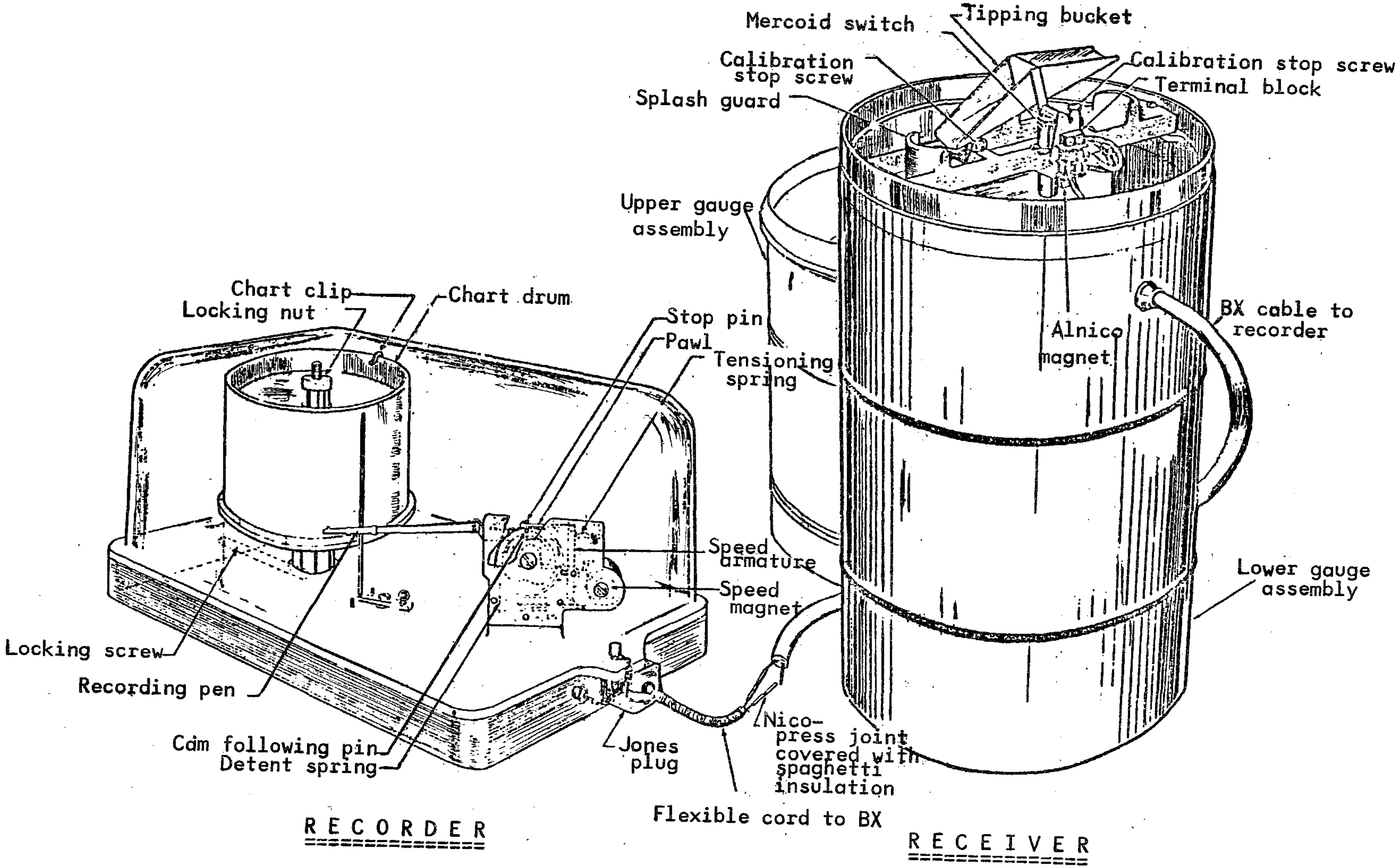


Figure 84 - Tipping-bucket rain-recorder

The tipping-bucket sensor and recording mechanism are connected by a two-lead cable. A direct digital indication of the precipitation amount can be obtained through the use of an ordinary counter driven by a suitable pulse-frequency divider.

The main advantage of the tipping-bucket precipitation recorder lies in its simplicity and the digital output of its sensor. The sensor is specially suited for use at automatic weather stations.

There are a number of shortcomings, however, inherent in the method. The most serious is the discrete nature of the information obtained, which is particularly noticeable with light rain and drizzle.

Another shortcoming is that the tipping motion takes time. During heavy rain, this leads to "overloading" of the bucket and an underestimated precipitation amount is thus recorded. By careful design, however, this source of error can be minimized, reducing it to one per cent at a rainfall rate of about 50 mm h^{-1} (very heavy rain).

The evaporation losses of the tipping-bucket sensor are appreciable in hot climates and in light rain.

One alternative design of an event precipitation sensor, similar in principle to the tipping-bucket, is the volumetric-valve type. This sensor, reduced to its essence, is a small cylindrical vessel provided with an electric valve at the outlet, which is controlled by an electric water-conductivity relay, whose electrodes are mounted in the upper part of the vessel.

As soon as the water entering the vessel reaches the electrodes, an electric current is passed through the water and an electric signal is obtained. The amplified signal opens the magnetic valve draining the vessel. Each draining cycle is counted (or recorded) and with a known volume of the vessel the precipitation amount is easily obtained.

The volumetric-valve type sensor makes for a smaller quantizing step (improved sensitivity), shorter discharge time (improved accuracy) and is less susceptible to evaporation losses.

The exposure of the tipping-bucket instrument (volumetric-valve type, also) is similar to that of the ordinary precipitation gauge discussed previously.

Sources of error in the sensor are:

- Evaporation of the precipitation catch (pronounced with light rain because of prolonged exposure of the catch between two tips of the bucket);
- Length of time of the tipping motion (error appreciable in heavy precipitation);
- Improper levelling of the instrument (change in volume of the content of the bucket).

The instrument is tested by pouring known amounts of water into the collecting funnel and observing the respective records. Differences in the amount necessary to tip the bucket in different directions may be a result of improper levelling or a lack of symmetry in the positioning of the tipping-bucket in its two stable states when empty. The adjustment is made by the two adjusting screws on the base-plate.

Generally, the tipping-bucket sensor keeps its calibration unless dirt or corrosion deposits have been introduced by the precipitation into the sensing element. Periodic inspection and cleaning is recommended.

In comparison to the two other sensors already discussed, the weighing-balance precipitation recorder is better as a measuring device for solid precipitation (Figure 85) and is predominantly used in cold climates.

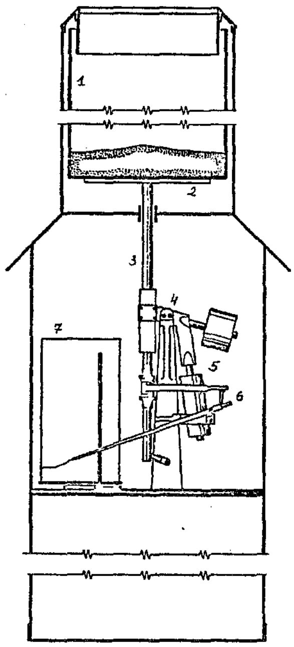


Figure 85 - Weighing balance rain-recorder

The weighing-balance precipitation recorder is based on the same principle as the ordinary counterweight letter-balance, used by many post-offices. A rod-supported (3) circular platform (2) carries the precipitation collector (1). By a parallel leverage, the rod itself is supported at two balance points by means of knife-edge supports. Counterweights (5) balance the collector assembly. Through a magnifying leverage (6) the motion of the rod, depending on the amount of the collected precipitation, is transmitted to the recording pen.

The recording chart's scale covers 35 mm of precipitation. This is the maximum amount which can be measured between two observations. The clock-driven drum (7) revolves once in 24 hours.

A cylindrical housing surrounds the collecting can and weighing mechanism. A sharp-edged rim defines the collecting area of the instrument. No funnel is provided for the collector, as this would impede the collection of solid precipitation. This is a disadvantage, however, when measuring the amount of liquid precipitation lost through evaporation, especially in hot climates. A remedy, albeit a partial one, may be the use of an evaporation-suppressing liquid such as oil.

Another disadvantage is the susceptibility of the weighing mechanism to oscillations initiated by gusts of wind, through an aerodynamic effect on the collecting orifice of the instrument. The precipitation records in strong winds are likely to be ill-defined and smeared, unless damping is used, or if the output is digitized using a circuit which removes the effect of such wind-induced oscillations.

The balance mechanism is sensitive to levelling and friction and needs periodic checks and maintenance.

An alternative design of the weighing-balance precipitation recorder makes use of a spring-loaded mechanism instead of counterweights, and an oil-damper to make the response of the instrument to wind gusts aperiodic. This improves the legibility of the records appreciably. A funnel is also provided with this version of the precipitation recorder, which can be mounted inside the collecting space as a measure against evaporation losses during hot weather.

There are no special requirements for the exposure of the weighing-balance precipitation recorder in addition to those already discussed in connexion with the ordinary precipitation gauge.

Sources of errors are:

- Excessive friction in the balance joints;
- Evaporation losses;
- Underdamping of the measuring system;
- Effect of wind and size distribution of drops in the precipitation event.

Periodic testing of the instrument using known amounts of water poured into the collecting can and observing the response of the weighing mechanism is recommended. Periodic cleaning of the collecting can and the application of very thin oil to the moving joints of the instrument will help to preserve its calibration characteristic.

6.2.3 The rate-of-rainfall recorder (Jardi)

The principle of operation of the rate-of-rainfall recorder is illustrated in Figure 86.

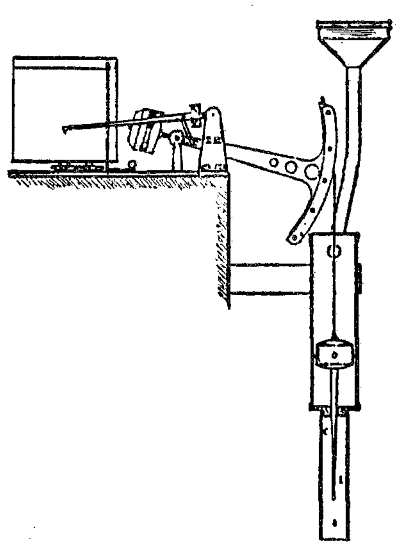


Figure 86 - Jardi rate-of-rainfall recorder

The collecting chamber of the instrument is provided with an annular outlet orifice in its base, the outflow of water from which is controlled by a specially-shaped, tapered rod attached to the bottom of the float. The rain-water collected by the funnel enters the chamber without falling on top of the float. With this arrangement, the outflow of water from the chamber will depend on the position of the tapered rod (acting as a valve), whose position in turn depends on that of the float, hence on the rate of inflow of rain-water.

The motion of the float is transmitted to the recording pen through a pivoted arm an a magnifying mechanism. The pivoted arm is provided with a counter-weight balancing the system almost neutrally, so that the recording mechanism follows the motion of the float without adding appreciable pressure to it. At each position of the float, corresponding to a definite rate of rainfall, there is equilibrium between the inflow and discharge of water.

The rate at which the water is discharged through the annular opening of the float chamber is proportional to the area of the opening and the square root of the depth of the water in the chamber. This rate is directly proportional to the rate of rainfall.

Let h be the height of the float above its zero position, R the radius of the annular opening and r the radius of the tapered rod at a distance h from the bottom of the float (r is a function of h). A linear scale of the instrument is required, thus the rate of rainfall w should be a linear function of h: $w = bh$, where b is a constant.

Also:

the depth of water = $(h + a)$, where a is a small constant

$$w = c(R^2 - r^2).\sqrt{h + a} \tag{1}$$

where c is a constant

$$r = \sqrt{(R^2 - \frac{A.h}{\sqrt{h + a}}} \tag{2}$$

where $A = b/c$.

If by wear and tear R increases slightly to $R + \Delta R$, ΔR being small, then

$$w = c\left[(R+\Delta R)^2 - r^2\right]\sqrt{h + a} \simeq c\left[R^2 - r^2 + 2R\,\Delta R\right]\sqrt{h + a} \tag{3}$$

The term containing $(\Delta R)^2$ has been neglected, being very small. Substituting the expression for r from (2) into (3) would give after rearrangement in the resulting relationship:

$$w = b.h + 2cR\,\Delta R\sqrt{h + a}\,. \tag{4}$$

When $h = 0$

$$w = 2cR\,\Delta R\sqrt{a} = w_o$$

which is the minimum rate of rainfall the instrument is capable of recording. In practice, w_o is 3 - 5 mm h^{-1}.

To allow for this initial lag, with no rain, the pen should be set to record the minimum rate of flow, w_o. With rates of rainfall above the value of w_o the instrument will record the true values. For larger rates of rainfall, however,

w_0 will be small in comparison with the second term on the right-hand side of equation (4) and corrections of the recorded values will be necessary. The corrections are best found by periodic calibration of the instrument. If water at a constant rate of flow is run into the collecting funnel of the instrument, its readings could be compared with the calculated values. Range of measured values: 5 - 150 mm h^{-1}.

The rate-of-rainfall recorder is sited and exposed to the measured variable in a similar way as all other precipitation-measuring instruments.

Sources of error are:

- Solid matter in the collecting chamber;
- Increased friction in the moving parts.

Periodic testing of the instrument is recommended. For the purpose of testing and calibration, a special instrument can be designed, capable of discharging water into the funnel of the rate-of-rainfall recorder at known and constant flow-rates.

6.2.4 Snow-measuring instruments

Measurements of snow at meteorological stations are aimed at determining the depth of snow cover and the snow liquid-water content. The snow-measurement data are of interest to the hydrologist and to specialists in agricultural production, aviation, road transport, etc.

Measurements of snow are made through the use of a number of instruments, among them: the snow ruler (depth of snow cover), snow gauge (liquid-water content), snow sampler (liquid-water content), snow pillow (liquid-water content), gamma-ray snow monitor (liquid-water content).

Measurements are made outside the meteorological station as well, mainly for the purpose of an areal estimation of the snow cover. These are known as a snow survey and are carried out along a so-called "snow course", consisting of a number of sampling locations. With a ten-point snow course the sampling is carried out at about every 50 m along a pre-determined 500 m line.

The exposure and siting requirements concerning the snow measurements are similar to those valid for a good precipitation-measurement site. Some of the requirements are contradictory and difficult to satisfy. The type of site which has been found to yield the most consistent results is an opening in a wooded area surrounded by hills for protection from high winds. The site should slope sufficiently to permit runoff of water from beneath the snow pack.

The snow ruler is an appropriately long, wooden ruler, mounted vertically at the measurement site. It is painted with a black and white "grid" pattern, each alternative white square being 1 cm x 1 cm and every tenth division being coloured red.

A number of snow rulers may be installed pre-selected at random, scattered throughout the site, the snow depth measurement being taken as an average.

The daily snowgauge is a simple collecting cylinder without a funnel. The collecting area of the instrument should be preferably 500 cm^2 or - even better - 1 000 cm^2 to reduce the chance of snow-capping or a reduction of the collecting area by ice formation. In order to prevent the collected snow from being blown out of the gauge, a can of depth at least three times its diameter is recommended. Two vertical partitions at right angles to each other, reaching down to the bottom of the can, called a snow-cross, would further prevent the collected snow being blown out by wind eddies inside the instrument.

The snowgauge should be exposed sufficiently high above the ground that its orifice is above the drifting level.

Two similar gauges are necessary for the measurement in order that a quick exchange of a full one for an empty one is possible at the time of observation.

The snow catch should be allowed to melt slowly indoors and the liquid content measured by a measuring cylinder.

The snow measurement is greatly affected by wind errors.

The snow-sampling set (snow sampler) is shown in Figure 87. The sampling tube is of metal and of known diameter (between 3.5 and 9 cm), provided with a saw-toothed cutter at its lower opening and a reinforcement ring with hole for the turning bar at the other end. The cutter is of a slightly smaller diameter, thus the cut snow-core is easily removed from the tube.

The tube is graduated in centimetres externally and slotted suitably to enable visual inspection of the snow-core.

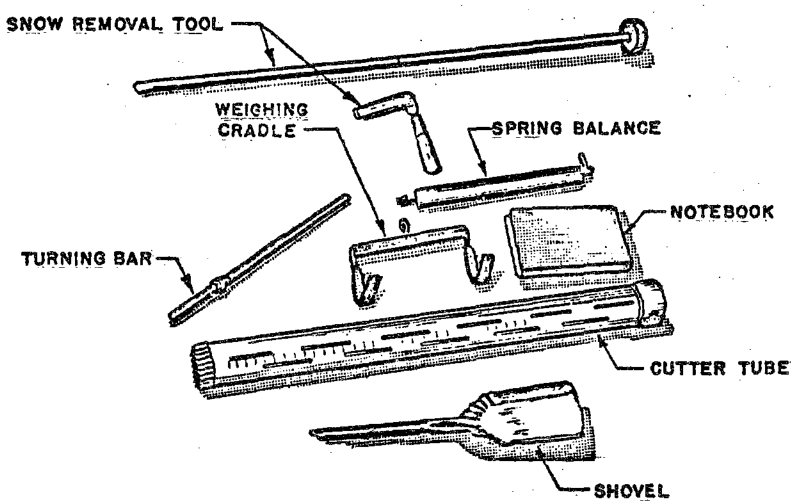


Figure 87 - Snow-sampling set

The sampler is driven vertically into the snow pack by the help of the turning bar until a "bite" in the ground is felt. Carefully withdrawn, the sampler is cleaned of litter and earth and the dirt plug removed. The snow-core is inspected through the slots of the tube and its length is read on the scale of the tube.

With a known weight of the empty sampling tube and its total weight with the snow-core measured on the spot with a spring balance, the snow density and liquid-water content can be calculated.

The snow pillow provides the means for a remote reading of the snow liquid-water content. In essence, it is a sturdy, inelastic, flat plastic bag of round shape of about 3.7 m diameter, filled with a non-freezing liquid. The snow pillow is placed flat on the ground at the site of measurement and is connected to a pressure-reading instrument through a small-bore pressure tube.

Because of its weight, the snow accumulated on top of the bag exerts a pressure on it, which is transmitted by the liquid along the tube to the measuring gauge, the scale of which is graduated directly in millimetres of water.

The accuracy of the method can be affected by the build-up on top of the snow pillow of a frozen, compact snow pack (effect of ice-bridging).

Radioactive gamma-radiation is attenuated by water. The attenuation of the natural gamma-radiation of the soil by snow cover can be used as a measure of the snow-water content (Figure 88).

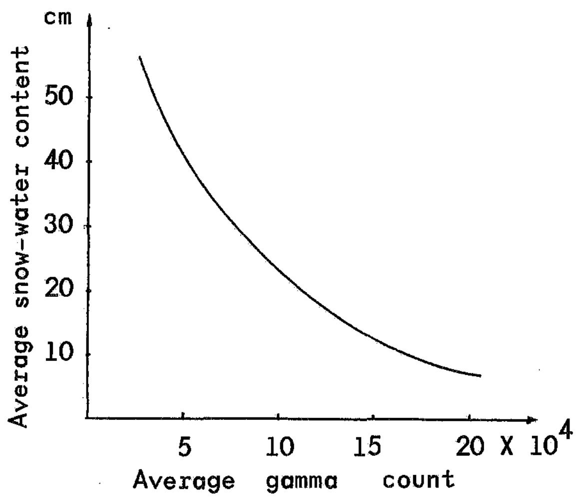


Figure 88 - Gamma-count versus snow-water content

<u>The gamma-ray snow monitor</u> uses a portable gamma-ray detector (Geiger-Müller counter) installed above the possible height of snow-drifting. A preliminary study of the radiation background on the spot without snow cover and a calibration of the device makes it possible to measure the snow-equivalent content within the limits of 5 to 45 cm with an error of about 1.5 cm.

A major source of error for the method is the unpredictable deposition (through precipitation or fall-out) of man-made or natural radioactive aerosols.

A further development of the method is the measurement of the natural radioactivity in specific energy bands. Introducing soil-moisture, altitude and air-density corrections and using an airborne (helicopter) radiation detector would enable the measurement to be carried out along a pre-determined snow course.

6.2.5 Dew-measuring instruments

For certain climatic conditions, dew constitutes an important part of the precipitation used by the vegetation. The amount of dew deposited depends on the meteorological conditions and the character of the underlying surface. There are relatively large variations in dew deposition over a given area, a fact which makes representative dew measurement particularly complicated.

One method of dew measurement is based on the increase in weight of a hygroscopic substance exposed to dew deposition during the early hours before sunrise. Gypsum and silica are such hygroscopic substances.

Duvdevani suggested a method based on the use of specially-painted wooden blocks exposed to dew; after its deposition they are compared with real-size photographic images of the block covered with known weights of dew.

The chief merits of the method are its simplicity and robustness. The main drawback of this and all methods is the uncertainty of the relation between the dew amounts recorded and those deposited on natural surfaces.

An instrument for a continuous recording of dew at the rate of its deposition has been suggested by Kyriazopoulos:

A long strip of highly glazed paper, coated with a thin layer of soot is wound by a clockwork mechanism from one drum to another. Only a short horizontal stretch of paper is exposed to the atmospheric conditions at any one time. It has been found that drops of dew, particles of hoar frost or drops of rain, each leave a distinct trace on the sooted surface of the strip. The recording gives the sequence of the formation of different forms of precipitation. It can, however, only give a rough indication of the intensity of the phenomenon.

The methods of measurement of dew described are not simple enough for routine applications.

6.2.6 Radar precipitation-measurement principle

The word radar is an acronym from the name of the method used in the detection of distant objects by radio waves: radio detection and ranging. Radar is a powerful means of observation in all conditions including those in which human vision is totally helpless. The objects observed by radar are known as radar targets.

Although initially created to meet military needs, radar has been found to have important meteorological applications in observing the weather as well as in the measurement of important atmospheric parameters.

Two main kinds of radar are used in meteorology:

(a) Doppler radar;

(b) Pulse radar.

The Doppler radar, as its name implies, is based on the use of the Doppler frequency-shift principle and its meteorological application for measuring the velocity of hydrometeors in storm cells is beyond the scope of this discussion.

The pulse radar is used, inter alia, for the measurement of the rate and amount of precipitation. It is a complicated electronic device but its operation can be explained in terms of the simplified block diagram shown in Figure 89. The device is considered as consisting of six functional blocks: modulator, transmitter, receiver, indicator, transmitter/receiver switch and antenna.

The modulator, through its modulation and synchronization pulses, controls the function of the other blocks.

The transmitter, controlled by the modulator, produces at its output high-power, high-frequency pulses of microsecond duration. The pulses appear at the output at regular time intervals of millisecond duration known as the pulse repetition period, T_r.

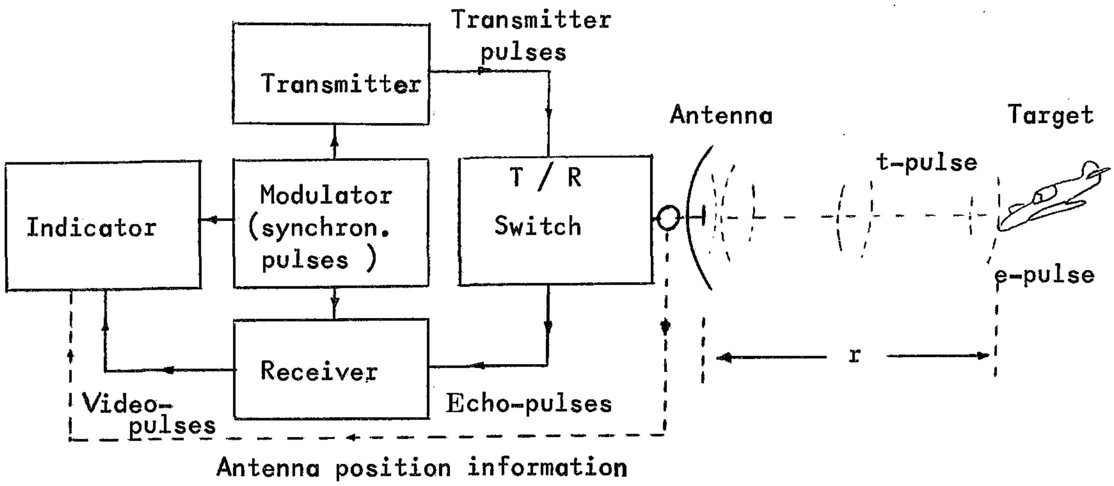


Figure 89 - Block diagram of pulse radar

Through a transmission line and the transmitter/receiver electronic switch (T/R switch) the pulses are passed to a highly directive antenna and are emitted into space in the direction of the radar target in a narrow-angle antenna beam.

During the transmission of each pulse the T/R switch connects the transmitter to the antenna, while blocking the input of the receiver in order to prevent damage from the very high transmitted power.

During the pause between pulses, the T/R switch connects the antenna to the input of the receiver, while blocking the output of the transmitter, in order to minimize receiver power losses.

The transmitted train of pulses of radio-frequency power travel through the atmosphere with the velocity of light ($c = 3.10^8$ m s^{-1}). On reaching a radar target, part of the energy of the pulses, depending on the target's back-scatter properties, is reflected back towards the radar antenna. These reflected pulses of much lower power level are known as "echo pulses". Each echo pulse would reach the antenna after a time interval $t = \frac{2.r}{c}$, taking into account the two-way excursion of the radio-frequency energy.

Reaching the antenna during the pause between two successive pulse transmissions, the echo pulse is amplified by the wide-band, high-sensitivity amplifier of the receiver to the necessary level for the operation of the radar indicator, based on the use of a cathode-ray tube. The pulses reaching the indicator are known as "video-pulses".

The simplest radar indicator, the A-scope shown in Figure 90 (a), displays the received pulse in an amplitude/time co-ordinated system, the time measured from the instant of transmission of the pulse. Since the distance between radar and target is proportional to the travel time of the pulse: $r = c.t/2$, the interval on the time axis of the scope between the images of the transmitted pulse and the received echo pulse represents the distance of the target from the radar. The amplitude of the echo pulse is a measure of the back-scatter properties of the target, proportional to its "radar cross-section".

The angular position of the antenna for maximum received power from the radar target gives the elevation and azimuth co-ordinates of the target, which together with the range, r, are the polar co-ordinates of the target.

In the case of a meteorological target, e.g. a precipitation zone, the information obtained from the radar would concern its spatial bearing, its motion in time, its size and its intensity.

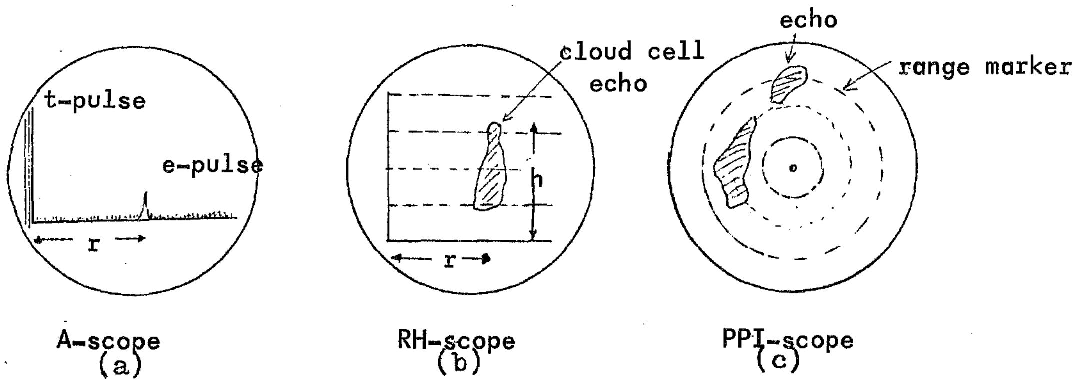


Figure 90 - Radar scopes (A, RH, PPI)

Three basic indicators are used in meteorological radar:

(a) The A-scope, already described;

(b) The range height indicator (RHI), giving a kind of vertical "section" through the meteorological target with its range and height above the ground (Figure 90 (b)) and a measure of its back scatter;

(c) The plan-position indicator (PPI), presenting a kind of "horizontal section" of the meteorological target (a map of the scanned area), with its bearing and back-scatter properties (Figure 90 (c)).

Depending on their specific application, meteorological radars operate in one of the frequency bands specified in the following table:

Frequency	Wavelength	Band	Typical meteorological application
1 500 MHz	20 cm	L	Radar-wind-balloon tracking
3 000 MHz	10 cm	S	Adverse weather warning, hail suppression diagnostics, precipitation measurement
6 000 MHz	5 cm	C	Weather radar, cloud investigation, precipitation measurement
10 000 MHz	3 cm	X	Cloud investigation
30 000 MHz	1 cm	K	Attenuation precipitation measurements

Meteorological radar parameters vary within certain limits. Typical meteorological radar parameters are given as an illustration:

- Pulse width T - about 1 μs;

- Pulse repetition frequency - $f_r = \frac{1}{T_r}$ is about 100 - 1 000 Hz;
- Peak transmitted power, P_t - about 250 kW;
- Receiver sensitivity - 10^{-12} - 10^{-14} W;
- Duty ratio = $\frac{T}{T_r} = \frac{\text{Average power}}{\text{Peak power}}$ = 0.001 (if T = 1 μs and T_r = 1 ms).

Radar is used in precipitation measurements in two ways:

(a) Based on the back scatter of the precipitation particles;

(b) Based on the attenuation of the radar beam by the precipitation particles.

Without going deeper into radar theory it should be mentioned that the following equation is used in precipitation measurement by the back scatter from the water droplets:

$$\bar{P}_r = \frac{\pi 5}{72} \left(\frac{P_t.\theta.\varphi.h.A_p^2}{\lambda 6}\right) \left|K\right| 2 \, \frac{Z}{r^2} \tag{1}$$

where:

$\bar{P}_r$ = average received power;

P_t = transmitted power;

θ,φ = horizontal and vertical angular dimensions of the antenna beam;

h = spatial length of the transmitted pulse (h = T.c);

A_p = antenna-dish aperture;

K = parameter connected with the complex index of refraction of the scatterer;

$$(\left|K\right|^2_{water} = 0.93 \text{ and } \left|K\right|^2_{ice} = 0.19);$$

Z = radar reflectivity, connected with the back-scatter properties of the radar target.

In the case of a meteorological target:

$$Z = \sum D^6 \ (mm^6/m^3) \tag{2}$$

D = diameter of cloud (rain) droplets.

An empirical expression for Z valid for most types of rain suggested by Marshall and Palmer is the following one (based on the relationship $Z = A.R^b$):

$$Z = 200 \ R^{1.6} \tag{3}$$

where:

R = rate of rainfall (mm h^{-1}).

For a specific radar set, within certain limits, the radar parameters may be considered constant and substituted in equation (1) by C, thus obtaining the simplified expression:

$$\bar{P}_r = \frac{C.P_t}{r^2} R^{1.6} \ (R \text{ in mm } h^{-1}) \tag{4}$$

Equation (4) relates the rate of rainfall in mm h^{-1} to the power received in watts and is the fundamental expression used in radar precipitation measurements. Without a correction for the attenuation of the electromagnetic waves due to precipitation it has a limited validity. Besides, the empirical relationship under (3) fails to cover all existing precipitation patterns. Relationships similar to equation (3) having different coefficients A and b have been suggested by a number of investigators for various precipitation patterns. This accounts for the actual accuracy of the radar method comparable in this respect with the point precipitation measurement using one raingauge per 300 km^2.

A remedial solution is the parallel use of radar and a small network of raingauges for updating the radar calibration through the equation $Z = A.R^b$. This method gives results superior to both the sole radar or raingauge use.

A different approach to the problem of radar precipitation measurement is through the use of the radar wave attenuation equation:

$$10 \log \frac{\bar{P}_r}{\bar{P}_{ro}} = 2 \int_o^z (k_g + k_c + k_p) dr \tag{5}$$

where:

k_g, k_c, k_p = the attenuation factors in db/unit range one way due, respectively, to gases, clouds and precipitation;

$\bar{P}_r$ = average received power (attenuated);

$\bar{P}_{ro}$ = average power which would have been received provided there was no attenuation.

For the purpose of precipitation measurement, equation (5) could be re-written as follows:

$$10 \log \frac{\bar{P}_r}{\bar{P}_{ro}} = 2 \int_o^z k_p dr \tag{6}$$

An empirical relationship suggested by Hitchfeld and Bordan for use with different wavelengths is the following one:

$$k_p = k_r . R^a \ (\text{db km}^{-1}) \tag{7}$$

where:

R = rate of rainfall in mm h^{-1}.

The value of k_r and a are given in the table for different λ:

λ (cm)	0.9	1.20	3.2	5.6	10
k_r	0.22	0.12	0.0074	0.0022	0.0003
a	1.00	1.05	1.34	1.17	1.00

Radar attenuation precipitation measurement poses definite practical problems, connected with the necessity of measurements along a pre-determined track.

From the two radar precipitation-measurement approaches the back-scatter method is the more versatile. Radar can integrate precipitation amounts over time and area by electronic means, so that its application to hydrological purposes (flood warning, dam control) is of great importance.

6.3 Exposure requirements concerning precipitation point-measurement instruments

The exposure requirements concerning the different point-measurement precipitation instruments have been discussed with each particular instrument. These requirements may be summarized as follows:

- The exposure of the precipitation instruments greatly affects their performance;
- The measurement of solid precipitation is affected by exposure to a greater extent than liquid precipitation;
- Wind speed and spatial drop-size distribution variations are the main contributors to precipitation measurement errors;
- Errors are increased by a departure of the plane of the receiving orifice from the horizontal;
- The instruments' exposure site should be sheltered from excessive wind turbulence, but shadowing of the instruments by large objects should be avoided.

6.4 Routine care of precipitation-measuring instruments

The most important points in respect of maintenance and testing of precipitation gauges may be summarized as follows:

- Periodic checks of the collecting orifice of the instrument for size and shape changes, especially after transportation;
- Periodic checks for leaks and corrosion of the collecting funnel and body of the instrument;
- Testing of the recording mechanism of recording precipitation gauges for changes in the position of the zero baseline and measuring range of the instrument.

Weak spots of the syphon gauge are the float and the syphon tube.

Weak spots of the weighing-balance precipitation recorders are the knife-supported joints and the dampers.

6.5 Factors affecting the accuracy of point-precipitation measurements

The commonly-accepted method of point precipitation measurement using can-type gauges exposed above ground-level is subject to appreciable systematic error - as much as 30 per cent or more - connected with the following factors:

(a) Wind-field deformation above the gauge rim and the different catching efficiency of the gauge's orifice for precipitation particles of different diameters. The loss of precipitation is known as wind error;

(b) Losses of precipitation from wetting of the internal walls of the collector and in the container - wetting error;

(c) Losses due to evaporation of collected precipitation in the container - evaporation error;

(d) Losses due to splash-out or rain drops;

(e) Losses due to blowing and drifting snow.

As these components of the systematic error vary with the type of instrument and the meteorological factors to a great extent, not all of them need be taken into consideration for each gauge type, season and region.

A method of correction for the first three components of the systematic error (wind error, wetting error, evaporation error) is briefly outlined below. (For more detail see Methods of Correction for Systematic Error in Point Precipitation Measurement for Operational Use - (WMO-No. 589).)

6.5.1 Wind-error conversion factor

Conversion factor, k, has been estimated experimentally, based on the assumption:

$$K = P_{gp}/P_{ge} \tag{1}$$

where:

P_{gp} = amount of precipitation measured in a sheltered gauge (e.g. a gauge mounted in a pit, with its collecting orifice flush with the ground, shielded with a grid against splash-in and splash-out, the pit provided with drainage against flooding from heavy precipitation);

P_{ge} = amount of precipitation measured in the exposed gauge (e.g. the elevated national gauge).

Both gauges should be of the same type, otherwise different wetting and evaporation losses must be taken into account.

The conversion factor, k, is a function of two variables: wind speed during precipitation at the level of the rim of the collecting orifice, u_{hp}, and the velocity of the falling precipitation particles. The latter depends on the structure of the precipitation.

The most important parameter for characterizing the structure of liquid precipitation is rainfall intensity, i_p. For periods of a month it can be assessed as a fraction N in per cent of the total amount of rain falling with an intensity $I_p \leqslant 0.03$ mm min^{-1}. The parameter N can be estimated directly from the records of recording raingauges, by adding together the precipitation amounts and the above intensities over ten-minute intervals. Values of the conversion factor, k, as a function of the wind speed, u_{ph}, and the parameters N and t for (a) liquid and (b) solid and mixed precipitation are presented in Figure 91.

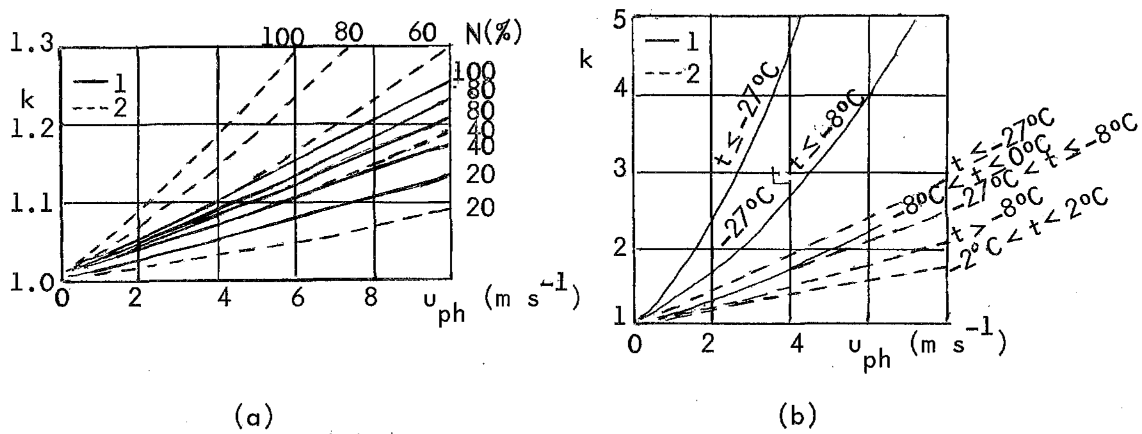


Figure 91 - Conversion factor k as a function of the wind speed during precipitation at the level of the gauge rim (u_{ph}) and the parameter of precipitation structure N and t for: (a) liquid precipitation; (b) mixed and solid precipitation; 1 = Hellmann gauge; 2 = Tretyakov gauge; t = air temperature during snowstorm

6.5.2 Wetting loss

The absolute value of the wetting loss depends on the geometry and material of the gauge collector and container, on the number of measurements of precipitation and on the amount, frequency and form of precipitation. It can be estimated as follows:

$$\Delta P_1 = a_1 . n_1 \qquad (2)$$

where:

a_1 = experimentally estimated average wetting loss per event for a particular collector and form of precipitation;

n_1 = number of precipitation events with the interval between them greater than the average time needed for the internal walls of the collector to dry out.

For the computation of monthly correction, a simplification is:

$$\Delta P_1 = \bar{a}_1 . M \qquad (3)$$

where:

a_1 = average collector wetting loss per day;

M = number of days with precipitation.

The total monthly wetting loss (one measurement per day) can be estimated from:

$$\Delta P_{tot} = \bar{a}_{1,2} . M \qquad (4)$$

where:

$\bar{a}_{1,2}$ = average wetting loss per day for a particular collector (a_1), container and other surfaces (a_2) and form of precipitation.

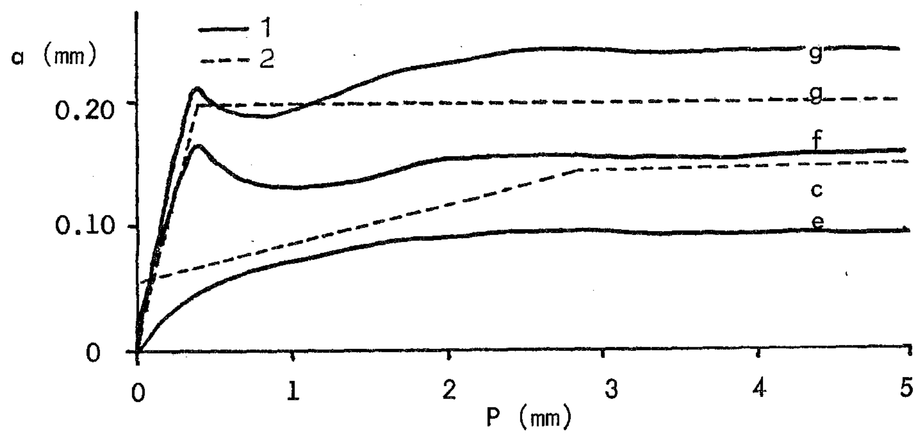


Figure 92 - Wetting loss per event (s_{mm}) as a function of precipitation amount (P). 1 = Helmann gauge; 2 = Tretyakov gauge. <u>Solid participation</u>: c = container and collector together. <u>Liquid and mixed precipitation</u>: e = container; f = collector; g = container and collector together

The value of the wetting loss per event a_1 and a_2 is different for liquid, mixed and solid precipitation and is usually estimated by weighing or volumetric measurements in a laboratory.

6.5.3 Evaporation loss

Correction for evaporation loss can be made using the relationship:

$$\Delta P_3 = i_e . T_e \qquad (5)$$

where:

i_e = intensity of evaporation (mm h^{-1});

T_e = duration of evaporation (h), time between end of precipitation and measurement.

The intensity of evaporation, i_e, depends on the construction, material and colour of the gauge, the form and amount of precipitation, the saturation deficit of the air, d , and on windspeed, U_{eh}, at the level of the gauge rim during evaporation.

A field experiment to measure i_e can be carried out by two different methods one "active" and the other "passive". In both cases, the humidity, temperature and wind speed must be measured simultaneously. The active experiment is based on the measurement of the evaporation rate from a simulated amount of precipitation in the gauge at fixed times. In the passive experiment at least two gauges of the same type are installed at the same height above ground. One is measured immediately after the precipitation event and the other at fixed times.

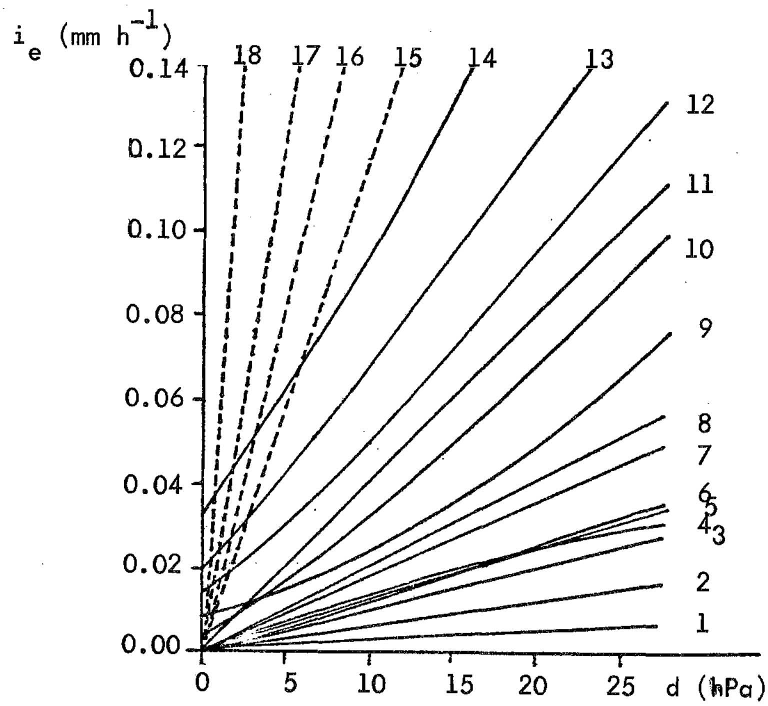


Figure 93 - Intensity of evaporation (i_e) versus air-saturation deficit (d) for various gauges (see text)

The values of i_e obtained by the active experiment carried out on the days without precipitation tend to be little greater than the results of the passive experiment.

The graphs, intensity of evaporation, i_e, versus air saturation deficit, d, (hPa) for various gauges are presented in Figure 93.

Intensity of evaporation for various gauges:

(a) Liquid precipitation:

(i) Australian standard gauge 1, 2, 7, 11 for $P \leqslant 1$ mm; 1.1 to 20 mm; > 20 mm and for wind speed $u_e < 4$ m s^{-1} and for $u_e \nless 4$ m s^{-1}, respectively;

(ii) Snowdon gauge in a pit 3, 6, 8 for $P \leqslant 1$ mm, 1.1 to 10 mm and > 10 mm, respectively;

(iii) Hellmann gauge 4;

(iv) Polish standard gauge 5;

(v) Hungarian standard gauge 9;

(vi) Tretyakov gauge 10, 12, 13, 14 for wind speed at the level of the gauge rim of 0-2, 2-4, 4-6 and 6-8 m s^{-1}, respectively;

(b) Solid precipitation:

Tretyakov gauge 15, 16, 17, 18 for wind speed 0-2, 2-4, 4-6 and 6-8 m s^{-1}, respectively.

Daily and monthly values of the evaporation correction ΔP_3 can be estimated if the average values of air humidity, temperature and wind speed during the period of evaporation are known.

CHAPTER 7

MEASUREMENT OF EVAPORATION

7.1 General - units of measurement

Evaporation is a physical process by which water from a wet surface or a free-water surface is brought into the air in the form of vapour at a temperature below boiling point.

Evaporation from vegetation is known as transpiration. The total combined loss of water from soil, water reservoirs and plants is called evapotranspiration, which is one of the main components of the water budget.

Evaporation from wet and free-water surfaces is a continuous process and is affected by the following factors:

- Heat supply (solar and terrestrial radiation);
- Vapour pressure gradient between the evaporating surface and the environment;
- Temperature of the evaporating surface;
- Wind speed at the evaporating surface;
- Size of the evaporating surface;
- Change of barometric pressure;
- State of the evaporating surface (if water, presence of waves, etc.);
- Content of soluble matter in the water.

In addition to these physical factors evapotranspiration is affected by the following plant factors:

- Type of vegetation;
- Depth of the active root zone;
- Total foliage and stomatal area (stomata - opening in the leaf surface).

The rate of evaporation is defined as the amount of water lost from a unit surface area in unit time. It can be expressed as the depth of liquid water in millimetres lost over the whole area per unit time.

7.2 Principles of evaporation-measuring instruments

Before discussing the various evaporation-measuring instruments used it is useful to mention briefly the main instrument classes:

(a) Atmometers - instruments making use of porous wet surfaces for the estimation of evaporation;

(b) Evaporimeters - pan or tank evaporation-measuring instruments;

(c) Evapotranspirometers - sunken tanks filled with soil and having the same vegetation cover as the adjacent area. The water lost through evaporation is measured by weighing;

(d) Lysimeters - instruments enabling the measurement of evapotranspiration as well as the loss of water through drainage in the soil.

7.2.1 The evaporation pan: Class-A pan - GGI-3000 pan - the elephant pan (20 m^2 tank)

The Class-A pan is circular, 1.21 m in diameter and 25.5 cm deep, filled with water to within 5 cm of the rim, and of area approximately 1.15 m^2. It is mounted in an elevated position, its base being 3 - 5 cm above ground, resting on a wooden platform, which permits air to circulate under the pan and facilitates the inspection of the bottom for leaks (Figure 94 (a)).

The water-level in the pan is measured by a hook-gauge, which consists of a movable scale and vernier with an attached pointed hook. To measure the change in water-level due to evaporation, the hook's pointed tip is made to just touch the water surface from underneath by turning the scale screw. The position of the hook is read on the scale and the value of the scale reading is subtracted from the previous reading. (The hook-gauge is surrounded by a stilling well which removes unavoidable wind ripples.)

The Class-A pan is constructed of either galvanized sheet-iron or Monel metal. The former is cheaper, but liable to corrosion and stains, especially if the pan-making process involves heating (welding). A modified version of the Class-A pan is installed sunken and protected from birds by chicken-wire mesh.

The GGI-3000 evaporation pan is again a cylindrical pan with a slightly conical bottom. The diameter is 61.8 cm (surface area 3 000 cm^2) and the depth 60 cm at the wall, 68.5 cm at the centre (Figure 94 (c)). The pan is made of galvanized iron-sheet and is installed buried in the ground with its rim 7.5 cm above the ground. In the centre of the pan there is a metal index tube upon which a volumetric burette is set when observations are carried out. The burette has a spring-loaded valve, which is opened by thumb pressure to allow the water-level in the burette to equal that outside. The valve is then closed and the volume of water in the burette is measured accurately. The height of the water-level above the metal index tube is determined from the volume of the water in the burette. A pointed indicator attached to the metal index fixes the height to which the water in the pan should be adjusted after the observation.

A GGI-3000 raingauge with a collecting area of 3 000 cm^2 is usually installed next to the pan.

The 20 m^2 elephant pan is a tank of 20 m^2 surface area, cylindrical in form (diameter 5 m, depth 2 m), made of 5 mm boiler-plate sheets and is an evaporation-measuring instrument whose readings come very close to free-water evaporation figures (Figure 94 (d)).

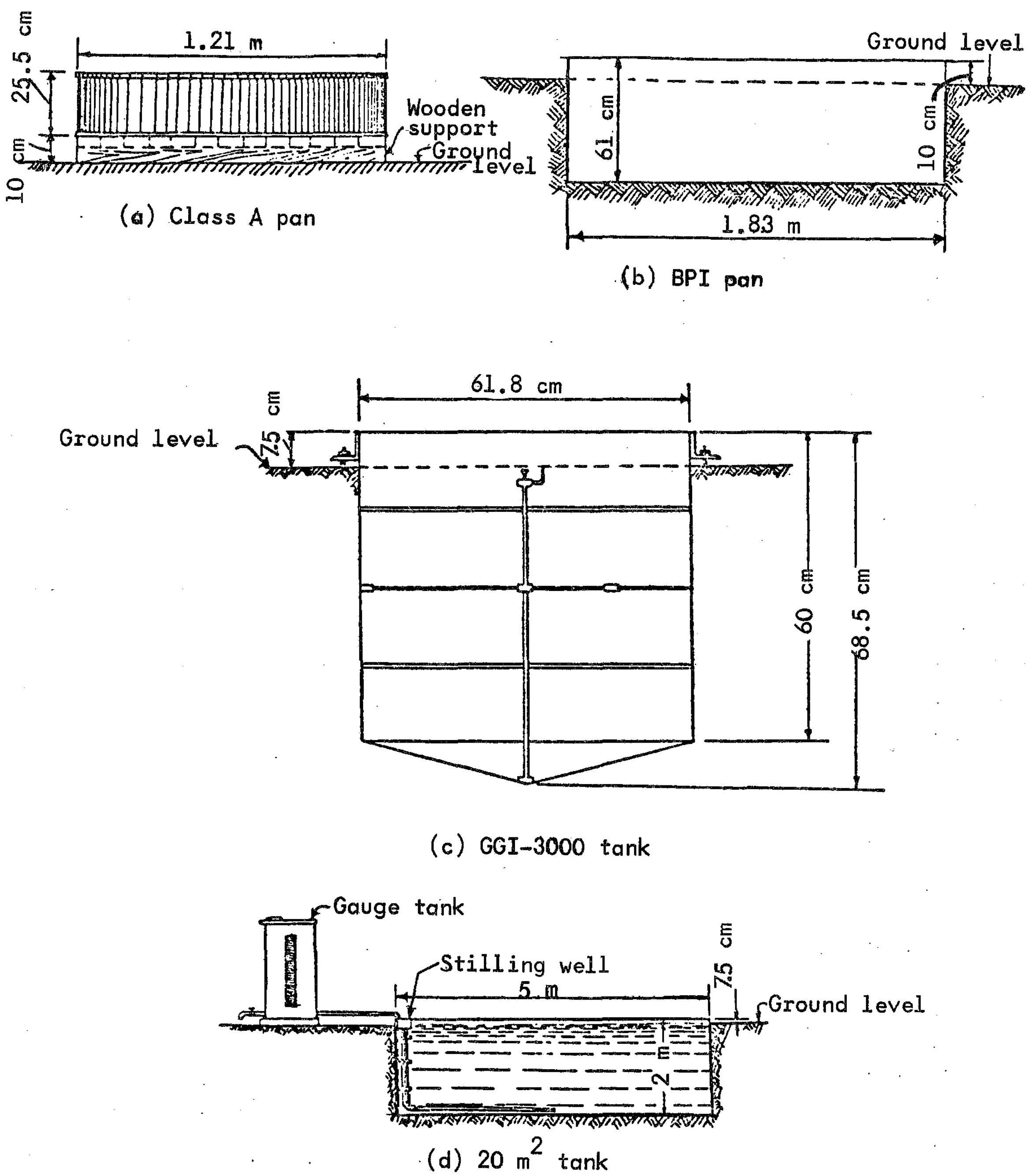


Figure 94 - Evaporation tanks and pans

The tank is installed in the ground with its rim 7.5 cm above ground-level. The water-level is maintained at approximately ground-level. An index pipe with a pointed indicator serves as a reference level-indicator. The water lost through evaporation is measured by the burette method already described in connexion with the GGI-3000 pan. Index pipe and point are surrounded by the wall of the stilling well.

The water in the tank is replenished from a water reservoir after the level has dropped by about 5 mm from the level indicated by the pointed extension of the index pipe.

Experiments have proved that evaporation from a basin containing water depends on a number of the basin's features:

(a) The size of the basin: evaporation rates from larger surfaces tend to be smaller than those from smaller surfaces. For example, with one and the same exposure, the evaporation rates from a 5 000 cm^2 basin is 20 - 30 per cent less than that from a 1 000 cm^2 basin (during the summer months). This phenomenon is explained by the so-called "edge effect" - increased evaporation rate from the edge of the basin in comparison to that from the rest of it. With circular basins, the edge effect could be expressed by the ratio of circumference to surface area:

$$\frac{2 \pi r}{\pi r^2} = 2/r;$$

(b) The shape of the evaporating surface: evaporation is greater from an elliptical surface than from a circular one. With an elliptical surface having an axis ratio of a/b = 4, the difference may be as much as 11 per cent;

(c) Exposure of the evaporating surface: an evaporating basin in a sheltered area evaporates less (about 40 per cent) than the same basin in the open;

(d) The colour of the basin's wall and bottom: white and shiny surfaces are related to lower evaporation rates.

The difference between the evaporation measured by an instrument and the actual evaporation, E_o, constitutes the evaporation-gauge correction coefficient: $R = E_o/E$ (unknown).

Evaporation pans may be used in experiments for the estimation of water-reservoir evaporation estimation if installed on floating platforms. The instrument is installed on a frame supported by a universal joint in order to diminish the effect of waves. The need for precautions is great. Parallel observations with a raingauge of the same collecting area are necessary in order to make corrections for the water added to the pan through precipitation.

Sources of error are:

- Changes in colouring of the pan walls and bottom due to rust or sediments;
- Birds, insects and other animals using the water of the pan for drinking;
- Unaccounted rainfall;
- Changes in temperature of the water;
- Undetected leaks.

The site for the installation of an evaporation pan should be open on all sides to permit free circulation of the air and should be fairly level. Obstructions (including trees) should be at a distance at least four times their height. Pans installed on the ground should be on a wooden frame and never on cement slabs or asphalt. The site should be covered with the same vegetation which is predominant in the surrounding area.

Sunken pans and tanks should be situated away from areas which may be flooded during rain and the ground water-level should be deeper than 2.5 m.

Floating platforms for measurements of lake evaporation should be situated at the upwind side of the water reservoir in order to avoid the effect of the lake evaporation on the pan evaporation, through advective changes of air humidity.

7.2.2 Atmometers - Piché - Livingstone porous porcelain types

One evaporation-measuring instrument using very small amounts of water and being immune to the effects caused by wildlife is the Piché atmometer. It has, however, numerous other shortcomings limiting its use to local evaporation surveys.

The principle of the device is illustrated in Figure 95. The Piché atmometer consists of a glass tube about 22.5 cm long, with one end closed. The internal diameter of the tube is about 11 mm and the thickness of the glass wall is about 3 mm. The open end of the tube is cut clean, so that a paper disk of diameter 3.2 cm fits closely to it, kept in place by a collared spring clip. In operation the tube, which is graduated in millimetres of evaporation consistent with the dimensions of the blotting-paper disk, is filled with water. The full tube is closed by the paper disk and clip arrangement and mounted in an inverted position in its own Stevenson screen.

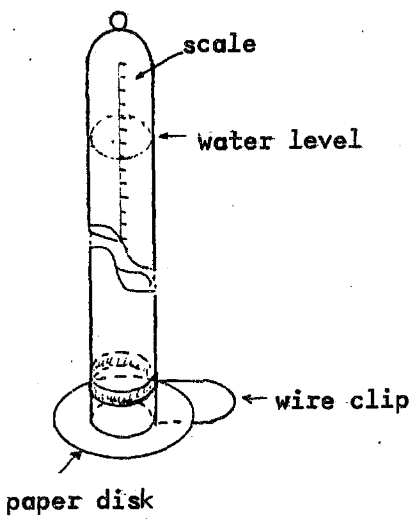


Figure 95 - Principle of the Piché atmometer

The water content of the atmometer is evaporated through the pores of the paper disk having an evaporating area of $S = 13\ cm^2$ (both sides).

If the tube's inner diameter is D_o and the cross-section area is S_o, the volume of the evaporated water, V, which is read from the graduations of the tube will be expressed as follows:

$$V = S_o . T \qquad (1)$$

where:

T = the observed scale-division difference.

The volume evaporated, V, will be a function of the evaporation potential, P, and the evaporating surface, S:

$$V = S.P \tag{2}$$

Combining equations (1) and (2) gives:

$$S_o T = S.P \tag{3}$$

therefore

$$P = T. \frac{S_o}{S} = T.F \tag{4}$$

where:

$F = S_o/S$

In spite of being inexpensive and convenient to handle, the Piché atmometer has only a limited use because of its deficiencies. The readings of the instrument are seriously affected by deposition of dust or sand on the filter-paper disk and by fluctuations in wind speed. A change of the quality of the blotting-paper or variations of its size affect the accuracy of the measurement of precipitation markedly and create difficulties in the standardization of the observations. Obtaining a correlation between the free-water surface evaporation and the readings of the Piché atmometer for the climatic conditions of the site can be used to improve the usefulness of the instrument for a larger-scale evaporation survey.

A smiliar principle to that used in the Piché atmometer underlies the operation of the <u>Livingstone porous porcelain sphere atmometer</u>:

A porous porcelain sphere attached to a glass tube is filled with water, the tube dipped into a reservoir of water. The atmospheric pressure on the surface of the reservoir keeps the tube and sphere filled with the liquid.

The amount of water evaporated from the surface of the sphere (diameter of about 5 cm) is obtained from the change of water content of the reservoir. As is the case with the Piché atmometer, distilled water is used. The Livingstone atmometer possesses the same shortcomings as the Piché instrument.

The following sources of error may affect measurement with atmometers:

- Water loss due to dripping (Piché atmometer);
- Changes in the evaporating surface (size, texture, cleanliness - Piché and Livingstone atmometers);
- Variations in the rate of ventilation.

Atmometers should preferably be exposed in their own Stevenson screen.

7.2.3 Evaporation-recording instruments

Attempts have been made to use evaporation recording instruments in a Stevenson screen, but these have been abandoned.

The principle of another approach is illustrated in Figure 96.

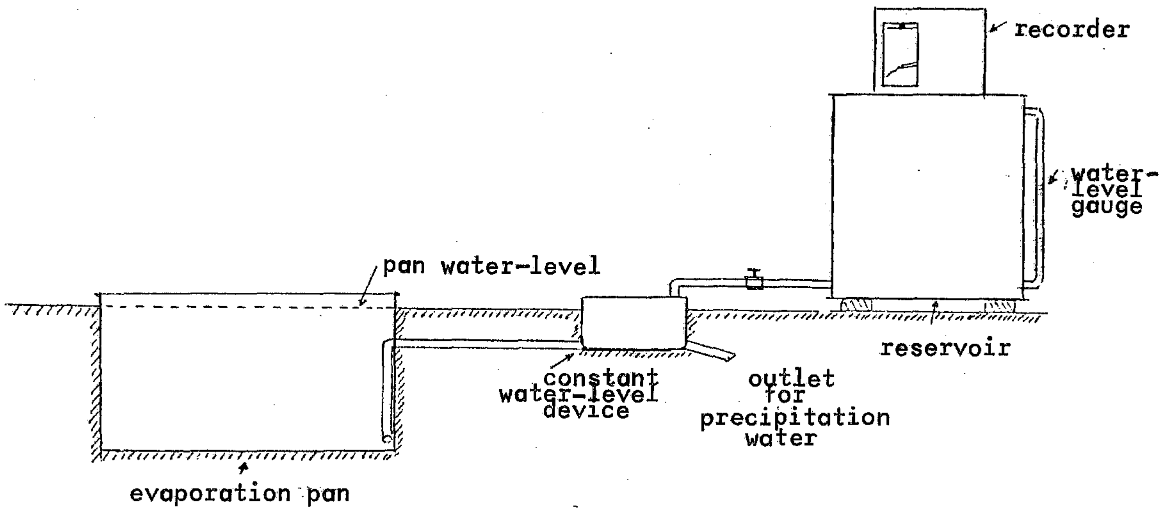


Figure 96 - Principle of Sumner automatic evaporation pan

The evaporation-recording instrument consists of four units: sunken tank, constant water-level device, replenishing water reservoir and float-type clock-driven recorder.

The important control function in the recording process is the constant water-level device, which is built on a principle similar to the constant-level chamber found in the carburettor of an automobile. It is a chamber and a float-controlled valve mechanism with a double function: to shut off the inlet-replenishing pipe when the water in the tank reaches the reference level, and to open a discharge outlet for water entering the tank from precipitation.

The replenishing reservoir is a cylindrical water container provided with a water-level gauge for direct readings of evaporation and a float mechanism for controlling the recording pen of the instrument.

The instrument is not in widespread use, mainly because of the need for a very accurate balance in the operation of the inlet and outlet valve mechanism which is very hard to attain. This precarious balance is one additional source of error, because the charge-and discharge-level difference in the control chamber must be kept within the limits of accuracy of the precipitation-measurement readings.

7.2.4 Evapotranspirometers

Evapotranspiration can be determined from the general equation of the hydrological balance, if the other factors are known. Thus, considering a block of soil: evapotranspiration = precipitation minus surface runoff minus underground drainage minus change in water storage of the soil block concerned. In the above equation, precipitation can be measured by standard methods; surface runoff can be collected from the investigated area and measured; underground drainage can also be collected and measured fairly easily but the measurement of water storage requires rather subtle gravimetric techniques.

If evapotranspiration measurements are to be reliable, the following requirements must be fulfilled:

(a) The design must be such that any disturbance caused by the presence of the evapotranspirometer is minimal. A relatively large buffer zone surrounding the measuring site should be available, covered with the same crop as the site. The structure of the soil inside the evapotranspirometer (or lysimeter) should be the same as that of the rest of the site;

(b) Soil moisture inside and outside the instrument should be kept at field capacity (through overhead sprinkling).

Evapotranspiration can be measured by a number of instruments which have been developed and by using the principle of the floating evapotranspirometer suggested by King, Tanner and Suomi (Figure 97).

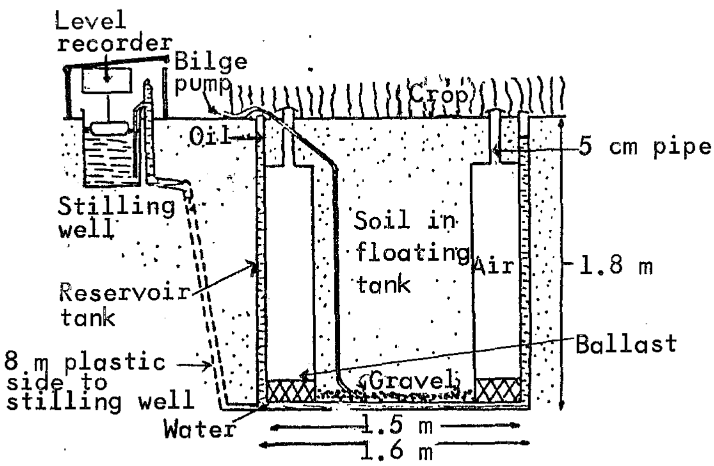


Figure 97 - Floating evapotranspirometer

The floating evapotranspirometer works on the Archimedes principle; and the balance is replaced by a hydraulic system. The soil container about 1.5 m in diameter and 1.8 m deep is floated in a suitable liquid in an outer container. Air-buoyancy chambers are foreseen in the construction as well as ballast for a steady floating balance.

A loss or gain in weight in the floating tank results in a change of level of the liquid.

If Δd is the equivalent depth of water loss owing to change of mass of the floating tank; A_s is the cross-sectional area of the floating tank; A_l is the area of the annular liquid surface plus the area of the stilling well; and S_l is the specific gravity of the liquid, then the application of Archimedes' principle leads to the following expression for the change in liquid level in the reservoir and stilling well, Δh:

$$\Delta h = \frac{\Delta d . A_s}{S_l (A_s + A_l)}$$

The water-level is recorded by a sensitive water-level recorder, such that weight changes are recorded accurately to the equivalent of ± 0.025 mm of evaporation.

To minimize evaporation from the reservoir and stilling well, 12.7 mm of transformer oil are poured on top of the water. A suitable syphon-damper is used to damp the oscillations obtained in a gusty wind.

Limitations of evapotranspirometers are:

(a) Effects of the instrument itself:

(i) Unrepresentative measurements because of the smallness of the instrument's dimensions (diameter and depth);

(ii) Wall and base effects (disturbance of thermal and moisture conditions; distortion of conditions at rim, distortion due to the wall, distortion of runoff conditions);

(iii) Effect of the disturbance of soil in filling (soil moisture tensions and heat flux);

(iv) Distortion owing to the unrepresentative vegetation cover;

(b) Effect of the siting (site unrepresentative of the area).

The evaporation-station plot, whose size depending on the number and type of installed instruments (at least 15 x 20 m), should be fenced properly to protect the instruments from animals, whilst enabling a free circulation of air over the instruments.

Water should be available and shelter necessary for the indicating/recording units of remote-reading instruments (if any).

A standard evaporation station provides for observations of precipitation, air temperature, wind speed and direction, and air humidity. It is strongly recommended that evaporation-pan temperature be measured as well.

7.3 General requirements for the evaporation-measuring instrument's exposure

These requirements may be summarized as follows:

- Open exposure and free circulation of air for the pan instruments and meteorological-screen exposure for the atmometers;
- Undisturbed conditions of evaporation and evapotranspiration taking into account heat-transfer factors by the pan instruments and in addition runoff, soil and plant factors by the evapotranspirometers.

7.4 Routine care of evaporation-measuring instruments

Evaporation-measuring instruments should be inspected periodically for the following flaws:

- Leakage of pan and tank instruments;
- Change in colour of walls and bottom of pans and tanks as a result of corrosion and sedimentation.

Pans and tanks should be cleaned regularly to remove litter, algae and sedimentation.

7.5 Comparability of measurement results obtained through different evaporation-measuring instruments

A WMO-initiated international evaporation instruments' comparison yielded interesting results about the comparability of evaporation measurement results obtained through different instruments in different conditions of climate and exposure.

A number of countries report on a ratio $\frac{\text{Class-A pan}}{\text{Piché atmometer}}$ evaporation ranging throughout the year from 0.68 to 1.35.

Average lake-to-pan (Class-A pan) evaporation has been found to vary from 0.67 to 0.81 depending on the site location.

The average monthly ratios $\frac{20\ \text{m}^2\ \text{tank evaporation}}{\text{pan evaporation}}$ have been found to vary for the GGI-3000 pan from 0.33 to 0.89 and for the Class-A pan from 0.66 to 0.73.

The effect of the site soil on evaporation is demonstrated by the evaporation ratio $\frac{\text{GGI-3000 in sand}}{\text{GGI-3000 in loam}}$. For the arid zone, this ratio is found to be 1.15 and for the humid zone 0.97.

The effect of screening the pan (2.54 cm (1 in.) chicken mesh) and painting it (bituminous black):

Class-A pan unscreened:	1.00	
Class-A pan screened:	0.86	$\frac{\text{Class-A pan unscreened}}{\text{Class-A pan screened, etc}}$
Class-A, screened and painted:	0.84	

The effect of the pan size (expressed through its diameter):

3.66 m diameter:	1.00	
1.83 m diameter:	0.91	
1.22 m diameter:	0.89	$\frac{\text{3.66 m evaporation pan}}{\text{smaller size evap. pan}}$
61 cm diameter:	0.81	
30.5 cm diameter:	0.86	

The effect of the colour of the pan walls and bottom: (new, galvanized, taken as reference): white - 82; orange - 92; light yellow - 93.3; aluminium - 97.6; dark blue - 101.6; dark green - 102.5; black - 105.7; copper (unpainted) - 106.7.

CHAPTER 8

SUNSHINE-DURATION MEASUREMENT

8.1 General

The amount of sunshine which is received in any area is one of the factors determining the climate of that locality. Agencies dealing with agriculture, forestry, tourism and recreation are especially interested in sunshine data.

The hourly or daily totals of the duration of sunshine obtained through measurement with an accuracy of one-tenth of an hour, using sunshine recorders, are an important climatological characteristic of the area of the measurement site.

An examination of long records of sunshine duration reveals differences in the monthly totals amounting to 20 per cent. These differences can be traced to the use of different instruments and techniques and to different climatic régimes. To reduce the discrepancy in sunshine records, a standard instrument has been recommended by the WMO, the so-called "interim reference sunshine recorder" (IRSR), with the understanding that all published sunshine values be reduced to the IRSR standard. A uniformity of $\pm$ 5% of the records is expected from the standardization practice.

8.2 Principles of sunshine-duration measurement

The existing sunshine-duration measuring instruments use either the heat energy of the Sun or its light energy. Four main types of instruments are available: (a) the Campbell-Stokes type, using solar heat to burn a trace on the recording chart; (b) the Marvin type in which the solar heat actuates a temperature-sensitive switch controlling the recording pen; (c) the Jordan type making use of a photographic process to record the sunshine; (d) the Foster type based on the use of a photoelectric switch to control the recording mechanism.

Types (a) and (c) act as sundials and require no clock for their operation.

The different sunshine recorders have a different minimum threshold value of solar radiation which is capable of initiating a record, ranging from a few tens of watts per square metre to as much as 400 W m^{-2}.

8.2.1 The Campbell-Stokes sunshine-duration recorder

This instrument was developed by Campbell as early as 1853. In its initial version it consisted of a spherical glass bulb filled with water, supported in the centre of a wooden-bowl segment. The solar radiation, focused on the inner surface of the bowl, burned a trace, giving an indication of sunshine duration. Stokes (1879) improved the instrument to its present-day design. A contemporary version is shown in Figure 98.

A glass sphere, made of high-quality, uniform, transparent glass (2) is supported in the middle of a gun-metal bowl, grooved to carry the record cards (Figure 99). The glass sphere of the standard pattern instrument has a focal length for sodium D light of approximately 75 mm. The sphere and bowl are supported by a sphere support (12), which is a tongue moving in a hinged cheek enabling the sphere and bowl assembly to be turned through a small angle, read-out on a latitude scale (5). The base-plate is attached to a sub-base-plate by means of three levelling screws, carrying lock-nuts (6). The base-plate can be turned in azimuth through a small angle, by means of the screw-and-slot adjusting arrangement (7). The sub-base-plate (11) is fastened firmly to the exposure standby bolts (through the drilled lugs (10)).

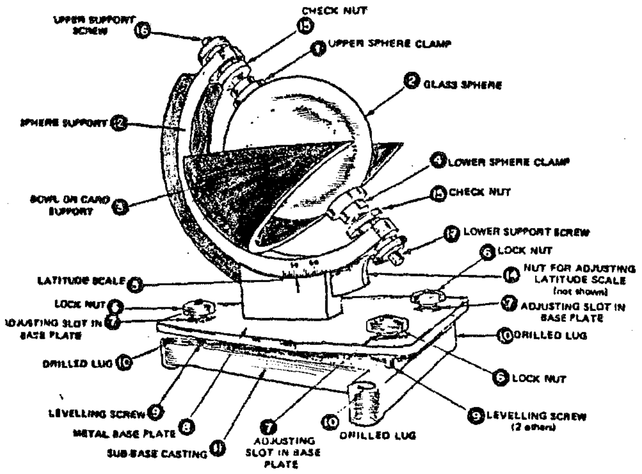


Figure 98 - Campbell-Stokes sunshine recorder

The instrument pictured in Figure 98 is designed for a principal latitude of 52°. A tropical model, which can be used in middle latitudes as well, is known as the universal pattern sunshine recorder (Figure 99).

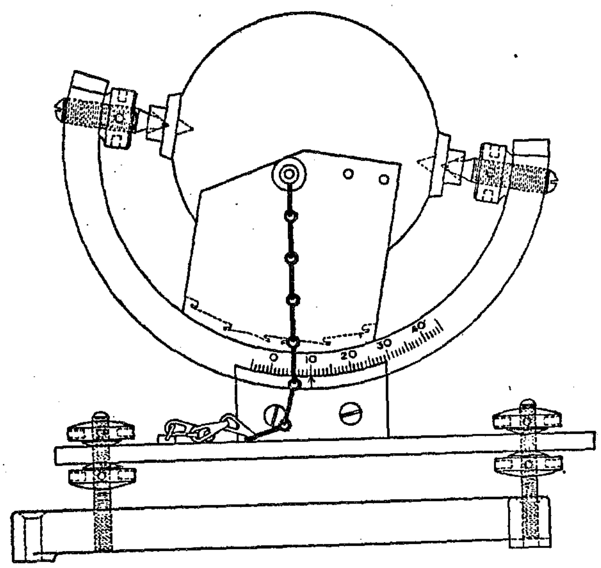


Figure 99 - Tropical model of sunshine recorder

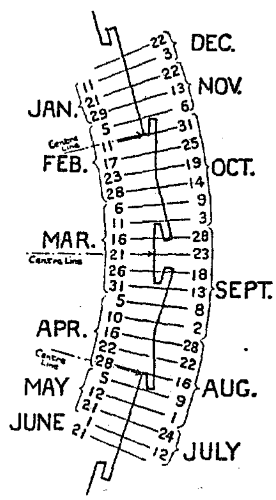


Figure 100 - Cross-section of sunshine recorder bowl & timing of cards

Inside, the bowl has special grooves into which are inserted the recording cards. Good-quality pasteboard, treated to be water-repellent and to have a specific low threshold is used for the recording cards. They are coloured pale blue in order to increase their radiation absorption. The cards, made accurately in width to within 0.3 mm and thickness to within 0.055 mm bear the sun-dial hourly graduations. These narrow margins of accuracy enable insertion and removal of the cards from the grooved bowl (Figure 100), even in humid weather.

Three types of card are used with the Campbell-Stokes sunshine recorder:

(a) Long, curved summer cards;

(b) Short, curved winter cards;

(c) Straight, equinoctial cards.

In moderate latitudes, summer cards are used from 12 April to 2 September and winter cards from 15 October to 28 February. The straight equinoctial cards are used the rest of the year.

Summer and winter periods vary with the geographical latitude and differ in timing during the year in each hemisphere.

Sunshine duration cards are changed every day after sunset.

Depending on the atmospheric conditions and the instrument itself, the minimum threshold value of solar intensity which will start a record is within the limits 70-300 W m^{-2}, which, translated into time after sunrise or before sunset, equals 10-20 minutes.

A free horizon is required over those sectors where the rising and setting Sun is close to the horizon. These sectors will vary according to the latitude of the observer. However, due to the relatively high threshold value of solar intensity necessary for recording to start, obstacles whose elevation above the horizon do not exceed 3^{o} may be neglected. A firm and level support is necessary for the instrument, capable of withstanding the weather extremes.

Before installation, the instrument should be inspected for defects and especially for concentricity of the sphere and bowl. This is best done with a centring gauge, which can be fitted into the equinoctial-card grooves of the bowl. The glass sphere needs no adjustment if its surface is equidistant from the arcs of the gauge (the distance is about one millimetre and eccentricity is easily established (visually)).

The installation of the instrument starts with the fixing of the sub-base-plate to the instrument stand with bolts, after rough orientation of the open side of the bowl to the south (in the southern hemisphere, the orientation is to the north). The base-plate is then levelled carefully, using a spirit level. The plane of the local meridan perpendicular to the Earth's surface should contain the sphere's axis and the noon mark on the bowl.

The latitude adjustment is easily made by moving the tongue in the cheek-hinge in the proper direction in order to make the latitude value of the site on the latitude scale coincide with the arrow mark on the cheek-hinge. If this is done correctly, then the axis of the glass sphere has the proper inclination towards the Earth's surface. The levelling, meridional and latitude adjustment may be repeated, if necessary, until the required accuracy of adjustment of the instrument is obtained.

If all adjustments have been made satisfactorily the burn trace should be parallel to the central line of the card and the Sun's image (focused light spot) should cross the bowl's noon mark exactly at the local apparent noon.

The sunshine recorder uses the movement of the Sun, instead of a clock. It is therefore necessary to know the relation of the position of the Sun and the standard of time actually used. The following definitions are useful in this respect:

<u>True solar day</u> is the time interval between two successive crossings of the Sun of the meridian of the place. The true solar day varies in length throughout the year.

Apparent solar time (AST) is the time based on the length of the true solar day.

Local apparent time (LAP) is the solar apparent time for any particular place, such that the Sun passes across the geographical meridian of the place at noon. This is the time indicated by the sun-dial.

Mean Sun-assumed day is the length of a mean solar day constant and equal to the average value of the true solar day taken over the whole year.

Local mean time (LMT) is local time based on the transit of the mean Sun across the meridian. Four times in a year LAP is equal to LMT (about 16 April, 13 June, 31 August and 25 December). At other times, a quantity known as the equation of time (ET) must be added algebraically to the local apparent time (LAP) in order to obtain the local mean time (LMT). The equation of time varies slightly from year to year but, for meteorological purposes, the values given in the table below are satisfactorily accurate. The values of the equation of time are given for every three days throughout the year to within half a minute:

Mean values of the equation of time (ET) (minutes)

Day	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	+3	+13.5	+12.5	+4	-3	-2.5	+3.5	+6	0	-10	-16.5	-10
4	+4.5	+14	+12	+3	-3	-2	+4	+6	-1	-11	-16.5	-10
7	+6	+14	+11	+2.5	-3.5	-1.5	+4.5	+5.5	-2	-12	-16.5	-8.5
10	+7	+14.5	+10.5	+1.5	-3.5	-1	+5	+5.5	-3	-13	-16	-7.5
13	+8.5	+14.5	+9.5	+0.5	-3.5	0	+5.5	+5	-4	-13.5	-15.5	-6
16	+9.5	+14.5	+9	0.0	-3.5	+0.5	+6	+4.5	-5	-14.5	-15.5	-4.5
19	+10.5	+14	+8	-1	-3.5	+1	+6	+3.5	-6	-15	-14.5	-3
22	+11.5	+14	+7	-1.5	-3.5	+1.5	+6.5	+3	-7	-15.5	-14	-1.5
25	+12	+13.5	+6	-2	-3	+2.5	+6.5	+2	-8	-16	-13	+0.0
28	+13	+13	+5.5	-2.5	-3	+3	+6.5	+1.5	-9	-16	-12	+1.5
31	+13.5		+4.5		-2.5		+6.5	+0.5		-16.5		+3

Civil (standard) time (CST) is local mean time for a standard meridian. Because the mean Sun "revolves" about the Earth at a rate of 1° in 4 minutes, at a station n° west of the standard meridian, its own meridian will be crossed by the mean Sun 4 n minutes after it has crossed the standard meridian.

The following equations are useful in the timing of the sunshine recorder:

$$\text{LAT} = \text{LMT-ET} = \text{ST} \pm 4\,(\lambda_s - \lambda)_{\min} - \text{ET}$$

where:

λ_s = the west longitude or the standard meridian;

λ = longitude of the station;

The sign (+) holds for the western hemisphere;

The sign (−) holds for the eastern hemisphere.

The above equation can be used in calculating the standard time of the local apparent noon (LAN):

$$LAN = 1200 + ET \pm 4\ (\lambda_s - \lambda)\ _{min}$$

where:

The sign (−) holds for the western hemisphere;

The sign (+) holds for the eastern hemisphere;

The estimation of LAN is necessary for the meridional adjustment of the sunshine recorder.

8.2.2 The Jordan and Marvin sunshine-duration recorders

The Jordan sunshine recorder is based on the chemical action of the visible and ultra-violet light of the Sun. The instrument consists of two semi-cylindrical cameras, mounted side by side, their flat sides facing the Sun, one oriented to the east and the other to the west. In the middle of each flat side of the cameras there is a small aperture, which passes the direct solar light to photographic paper (ferroprussiate type, insensitive to diffuse sky light) placed round the cylindrical wall of the camera (Figure 101).

The instrument requires adjustment for level, meridian and latitude very much as the Campbell-Stokes recorder but is less convenient to use.

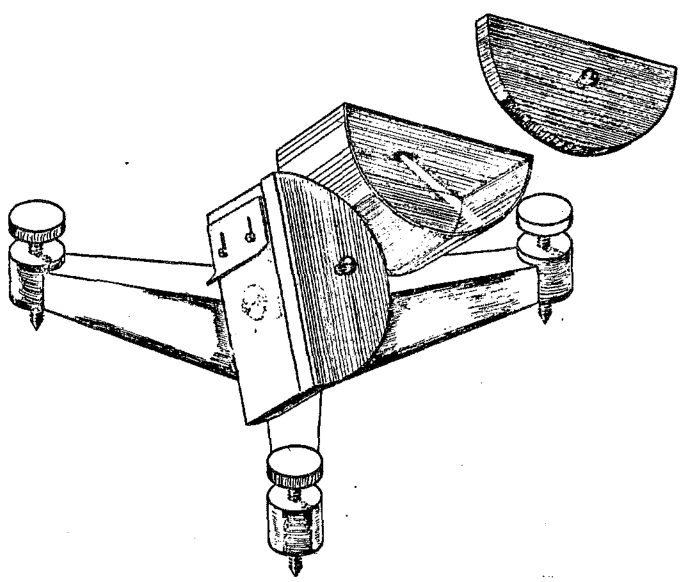


Figure 101 - Jordan sunshine recorder

The Marvin sunshine recorder is based on the use of a differential thermometer (Figure 102). Two air thermometers, one with its bulb blackened and the other clear, share the same glass jacket. The two thermometers are separated by a column of mercury. With the Sun shining, the blackened bulb absorbs more energy and its temperature rises more than the clear bulb. The separating mercury column moves towards the clear bulb, passing on its way the contact of an electrical circuit, which is thus short-circuited. The electric signal obtained operates a chronograph.

The Marvin sunshine-duration sensor is suitable for remote recording.

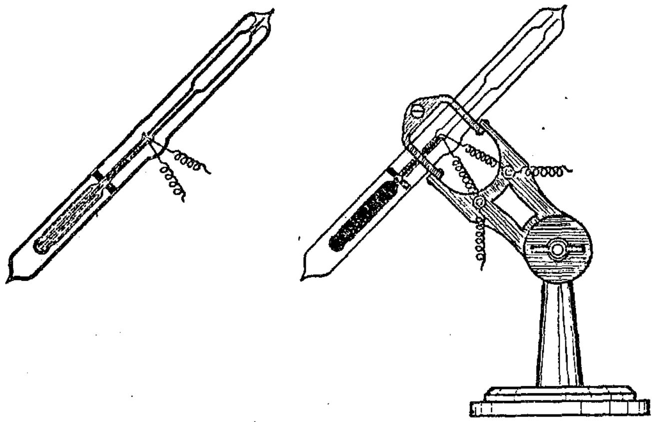


Figure 102 - Marvin sunshine recorder

Similar in principle is the Sumner sunshine-duration recorder. Its differential thermometer consists of a number of semicircular bimetallic contact pairs connected in parallel. The Sun heats the outer, blackened bimetallic strip to a higher temperature than the inner one. The outer strip bends; one or more of the pairs are closed and an electric signal is obtained, which operates a chronograph. The bimetallic contact assembly is sheltered from the weather by a glass dome.

A different principle underlies the Foster sunshine switch. This instrument uses shaded and unshaded photovoltaic cells, whose electrical signal operates the chronograph.

8.3 Siting and exposure requirements for sunshine-duration measuring instruments - factors affecting the sunshine records of the Campbell-Stokes instrument

The exposure requirements can be summarized as follows:

(a) A new site should be available for use for at least ten years;

(b) The surroundings of the site during its operational life should not change significantly;

(c) The site should have an open horizon to the east and west with no obstruction to the Sun's rays having an elevation higher than 5^{o} any time in the year.

The following factors may adversely affect the sunshine-duration records:

(a) Disturbed concentricity of glass sphere and bowl;

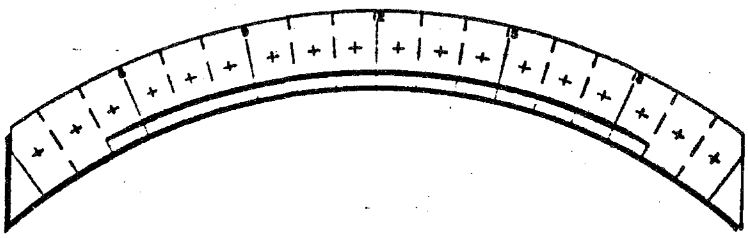
(b) Levelling, meridional and latitude errors in the adjustment of the instrument;

(c) Defects or dirt in the glass sphere;

(d) Environmental effects on the instrument.

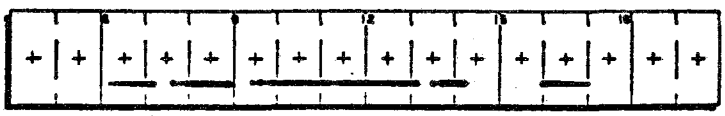
Properly-taken sunshine records are presented in Figure 103. The faults encountered most often are presented in Figures 104, 105 and 106. The illustrations (which are reproduced here at half-size) are self-explanatory.

(a)



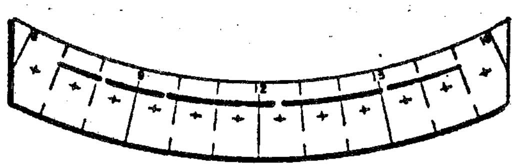
NOTES: (1) Burn obtained on 13 July (summer card).
(2) Burn is parallel to cross-marks.
(3) Burn would be 10 mm below the cross-mark if the illustration were full size.
(4) Sunshine was continuous from sunrise to sunset; therefore, the length of burn before the "noon-mark" is equal to the length of burn after the "noon-mark".

(b)



NOTES: (1) Burn obtained on 11 October (equinoctial card).
(2) Burn is parallel to cross-marks.
(3) Burn would be 10 mm below cross-marks if the illustration were full size.

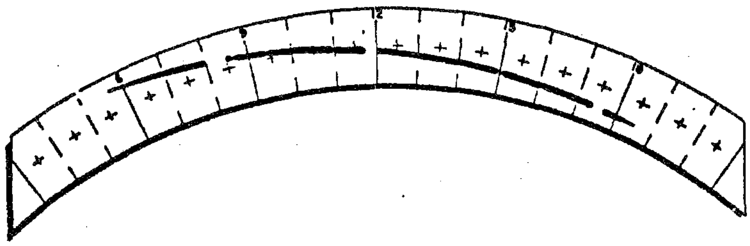
(c)



NOTES: (1) Burn obtained on 15 October (winter card).
(2) Burn is parallel to cross-marks.
(3) Burn would be 7 mm above cross-marks if the illustration were full size.

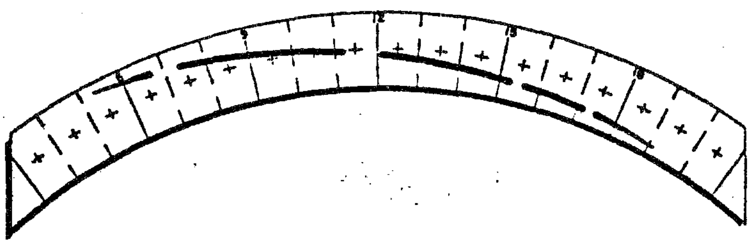
Figure 103 - Cards of a sunshine recorder, properly installed and adjusted

(a) Recorder NOT level - east-west (otherwise properly adjusted):

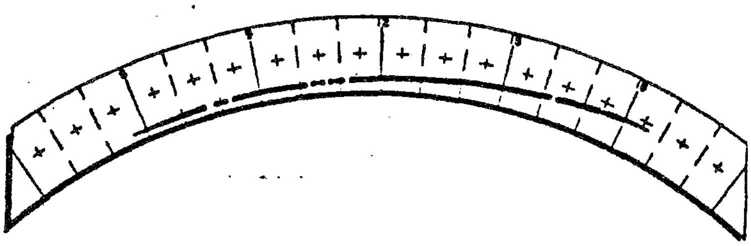


The above trace was obtained on 1 July from a recorder which was out of level - east-west. (In this case the west side of the recorder was too high).

(b) Recorder NOT properly set for local apparent noon (otherwise properly adjusted):

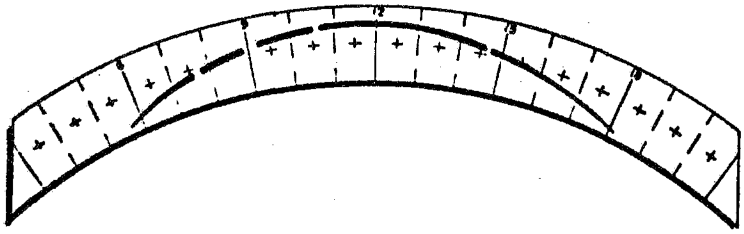


(1) The above trace was obtained on 12 July from a recorder on which the adjustment for local apparent noon was in error by 30 minutes. (In this case the image of the Sun coincided with "noon mark" 30 minutes earlier than it should have.)

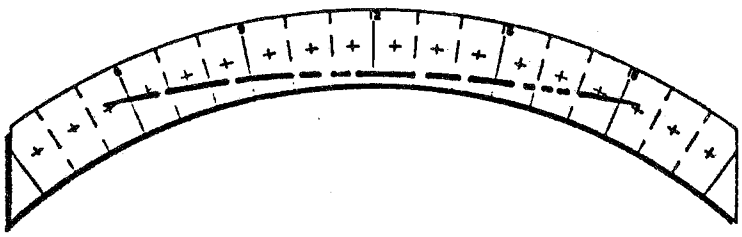


(2) The above trace was obtained on 16 July from a recorder on which the adjustment for local apparent noon was in error by 20 minutes. (In this case the image of the Sun coincided with "noon mark" 20 minutes later than it should have.)

Figure 104 - Cards of improperly adjusted sunshine recorder



(1) The above trace was obtained on 29 July from a recorder on which the latitude setting was in error. The scale reading was set 5° lower than the actual station latitude.



(2) The above trace was obtained on 30 July from a recorder on which the latitude setting was in error. The scale reading was set 5° higher than the actual station latitude.

A trace which is broad and ill-defined at the edges and which is in the correct position at the equinoxes, i.e. 21 March or 23 September, but not parallel to the cross-marks at other times of the year, indicates poor adjustment for concentricity. This adjustment cannot be corrected in the field.

Faulty adjustment may cause serious loss of record at certain times of the year through the burn or scorch running off the edge of the card.

Example:

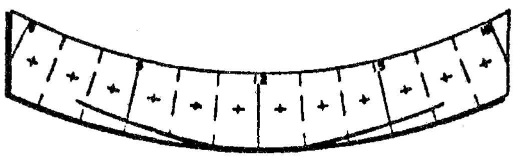
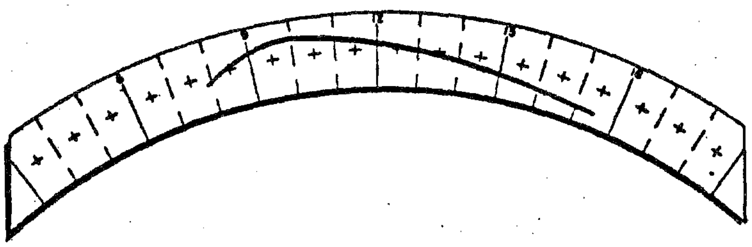


Figure 105 - Cards of a recorder having latitude-setting error



The above trace, which is neither symmetrical with respect to the "noon mark" nor parallel to the cross marks, indicates that:

(1) Two or more of the adjustments are in error;

(2) The recorder should be re-adjusted for level, latitude and longitude.

Figure 106 - Cards of a recorder needing levelling, latitude and longitude adjustment

8.4 Routine care of the Campbell-Stokes sunshine recorder - measurement of burn trace on the cards

The instrument is a durable one and needs very little attention. The glass sphere needs periodic cleaning and the cleaning procedures have to be carried out with great care so as not to spoil the transparency of the sphere. In conditions of abrasive dust and sand pollution of the air, the glass sphere is brushed lightly first with a soft camel-hair brush then cleaned with a chamois leather and alcohol.

The bowl is cleaned in the conventional way using detergent and water. Birds' droppings should not be scraped off, but washed off thoroughly.

The grooves of the bowl are cleaned with a tapered piece of wood and then washed with water.

Wintertime maintenance of the Campbell-Stokes sunshine recorder is reduced to removing frost, snow or ice. These are readily removed by applying a 50/50 solution of water and ethylene glycol or any harmless de-icer. The excess fluid should be carefully wiped off the sphere with a cleansing tissue.

The holes for draining the rain-water, to be found at the intersection of each groove with the noon mark, should be cleaned with the same pointed wooden stick used for cleaning the grooves. Failure to do this leads to a retention of rain-water in the bowl, soaking the record cards and spoiling the records.

The groove and draining-hole cleaning is carried out more conveniently with the glass sphere removed. Care should be taken to leave the sphere on a soft cloth on the ground. When placing the sphere back in place, care should be taken not to disturb the concentricity of the glass sphere and bowl: the sphere should be removed by loosening only the upper screw after releasing the lock nut.

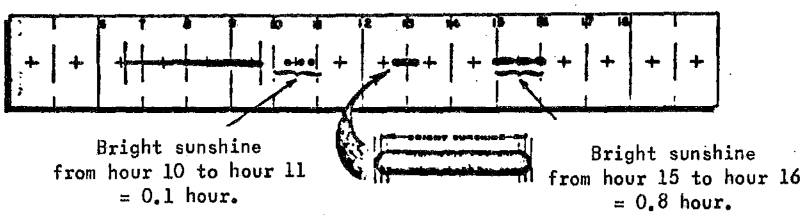


Figure 107 - Estimation of spread of burn on card

The amount of bright sunshine is expressed in tenths of an hour. The measurement of the burn trace is best done with the help of a special scale made of transparent material and graduated in tenths of an hour.

Intermittent burn traces are measured, allowing for the smouldering of the card and some lateral spread of the burn. Allowance must be made by measuring each burn to a point half-way between the extreme edge of the burn and the centre of curvature of the rounded extremity.

Faint scorch marks are measured to the extreme ends of the trace. With circular burns, it should be considered that two or three of them are the equivalent of 0.1 hour of sunshine.

C H A P T E R   9

SOLAR-RADIATION MEASURING INSTRUMENTS

9.1 General - units of measurement

Solar radiation is of the utmost importance to life on Earth. The different radiation fluxes to and from the Earth's surface are terms in the heat budget of the Earth as a whole and of any particular place on the globe. Radiation measurements are of great value to science, industry, agriculture, etc.

The spectral distribution of the intensity of the solar extraterrestrial radiation covers a band of frequencies from the ultra-violet through the visible light to the infra-red. Recent studies have produced an improved spectral distribution but the results have not yet been published. The graph in Figure 108 stemming from older sources gives an idea of the spectral distribution (curve 1). In the same figure, the intensity of the direct solar radiation at sea-level and at 35° height above the horizon of the Sun is given for comparison (curve 2). The intensity of the longwave, terrestrial radiation, on the assumption of an Earth's surface temperature of 20°C is shown by curve 3. The wavelength of the radiation is in micrometres. Approximately 99 per cent of the radiation emitted by the Sun, assumed to have a surface temperature of 5 800°K lies in the range 0.15 - 4.0 μm. Almost 45 per cent of the total solar emission occurs in the visible band and as much in the infra-red. About nine per cent occurs in the ultra-violet band.

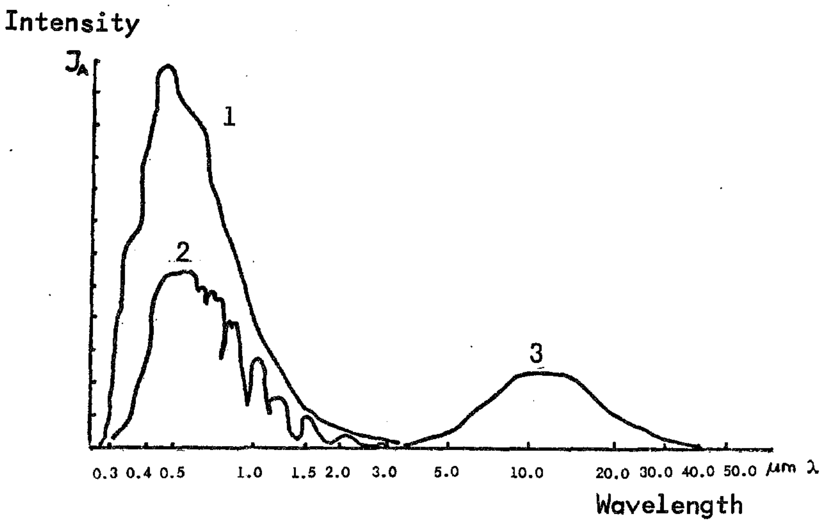


Figure 108 - Extraterrestrial radiation spectral distribution

Radiation from the Earth to space is in the range of 4 - 100 μm (temperature about 200° to 300°K) with a maximum at about 10 μm. This radiation is known as terrestrial radiation.

In order to be capable of measuring radiation, the instrument's sensor must be a good absorber of radiative energy. A special kind of black lacquer is used to paint the radiation-absorbing surface of the sensor. A hypothetical body, which absorbs completely all the incident radiation is referred to as a "black body". Perfect absorbers of radiation over the total wavelength range do not occur in nature. With their specially-painted surface the radiation instrument sensors come very near to a black body for the waveband they are used to measure.

Good absorbers of radiation are also good emitters of radiation. The hypothetical black body emits radiation at all wavelengths according to the law:

$$E_T = \sigma T^4$$

where:

$\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4} (Stefan-Boltzmann constant);

T = temperature in kelvins.

The black-body emission calculated from the above formula for various Celsius temperatures is as follows:

t^o ^{o}Celsius	-60^o	-40^o	-20^o	0^o	20^o	40^o	60^o
E_T W m^{-2}	119	168	237	321	426	551	712

The emissivity of the Earth depends on the characteristics of its surface. The energy radiated has a maximum at a specific wavelength depending on the radiation temperature of the surface. The wavelength of the maximum radiation can be found from Wien's displacement law:

$$\lambda \max = \frac{C}{T} \text{ (m)}, \ C = \text{const.} = 0.2898 \times 10^{-2} (\text{m } ^oK^{-1}).$$

Solar and terrestrial radiation components are of considerable interest to meteorology. The following solar radiation components penetrating the lower layers of the atmosphere are subject to measurement for meteorological purposes:

(a) Direct solar radiation measured at normal incidence;

(b) Global solar radiation received on a horizontal surface. This includes both the radiation received from the solid angle of the Sun's disk and the radiation diffusely scattered by the intervening atmosphere;

(c) Sky radiation. This is the second component of the global radiation already mentioned above;

(d) Reflected solar radiation;

(e) The solar radiation (direct, global and sky) measured in restricted portions of the spectrum;

(f) Measurement of solar radiation falling on a spherical surface;

(g) Measurement of the solar radiation falling on a fixed surface other than horizontal.

From all seven enumerated solar radiation components, those under (a), (b), (c) and (e) are of more general interest.

In some countries the solar radiation flux is measured in calories per square centimetre per minute (one calorie per square centimetre being known as a Langley), but the S.I. unit for measurement of the radiative flux per unit area is the watt per square metre ($W\ m^{-2}$) and, for radiation amount per unit area: joules per square metre ($J\ m^{-2}$). The conversion factors for solar radiation units in use are as follows:

Irradiance	To convert to $W\ m^{-2}$ multiply by:
$mW\ cm^{-2}$	10.0
$kW\ m^{-2}$	1 000.0
$cal\ cm^{-2}\ min^{-1}$	697.8
$mcal\ cm^{-2}\ s^{-1}$	41.868
Radiant exposure	**To convert to $J\ m^{-2}$ multiply by:**
$J\ cm^{-2}$	10 000.0
$cal\ cm^{-2}$	41 868.0

(See Guide to Meteorological Instruments and Methods of Observation, 5th edition, chapter 9.)

9.2 Solar-radiation measuring instruments

Before entering into a discussion of the different instruments for measuring solar-radiation components, the internationally-accepted classification of these instruments will be considered:

A pyrheliometer is an instrument for measuring direct solar radiation at normal incidence. There are primary (standard) pyrheliometers and secondary pyrheliometers scaled by reference to a primary one.

A pyranometer is an instrument for measuring solar radiation emanating from the total hemisphere. It is used for global radiation measurements and, together with a shade-ring attachment, for sky radiation measurements.

A pyrgeometer is an instrument for measuring net atmospheric radiation on a horizontal, upward-facing black surface at the ambient air temperature.

A pyrradiometer is an instrument for measuring both solar and terrestrial radiation.

A net pyrradiometer is an instrument for measuring the net flux of downward and upward total radiation through a horizontal surface.

The radiation instruments are ranked in different classes according to their measurement characteristics (see Guide to Meteorological Instruments and Methods of Observation, 5th Edition (WMO-No. 8)).

On the basis of recent determinations reported by Brusa and Frölich (1980) the CIMO Working Group recommends acceptance by WMO of a value of the solar constant of 1.367 $\pm$ 0.007 $kW\ m^{-2}$. The uncertainty arises partly from uncertainty in the determination and partly in tracing the value to the World Radiometric Reference (WRR).

All radiation measurements are referred to Local Apparent Time (LAT).

Many radiation instruments incorporate thermopiles as their sensitive elements and the output is measured as small electromotive forces. The measuring instrument to be used depends on the range of the signal expected, requirements concerning accuracy and sensitivity and the input resistance of the measuring instrument. For instantaneous measurements, portable potentiometers are often preferred and for less precise work, the sensor of the instrument can be connected to a pointer-type millivoltmeter (microamperemeter). For continuous records either recording millivoltmeters or self-balancing electronic potentiometers are used (see Part 3 Matching of indicating/recording instruments to electrical sensors).

9.2.1 Direct solar-radiation measuring instruments

Direct solar radiation is measured by pyrheliometers, the sensing surfaces of which are exposed normally to the Sun's rays. By the use of diaphragms, only the radiation from the solar disk and a very small annulus of the sky is measured. The instruments are pointed towards the Sun using an aiming device and adjusted in azimuth and elevation through a special gear.

Continuous records with direct solar radiation instruments are possible through a motor-driven equatorial mount, which is capable of following the Sun's "rotation around the Earth" with great precision.

The Ångström electrical compensation pyrheliometer (introduced by K. Ångström) is one of the most reliable instruments for measurement of direct solar radiation (Figure 109). Its principal use is as a primary working standard for the calibration of secondary pyrheliometers.

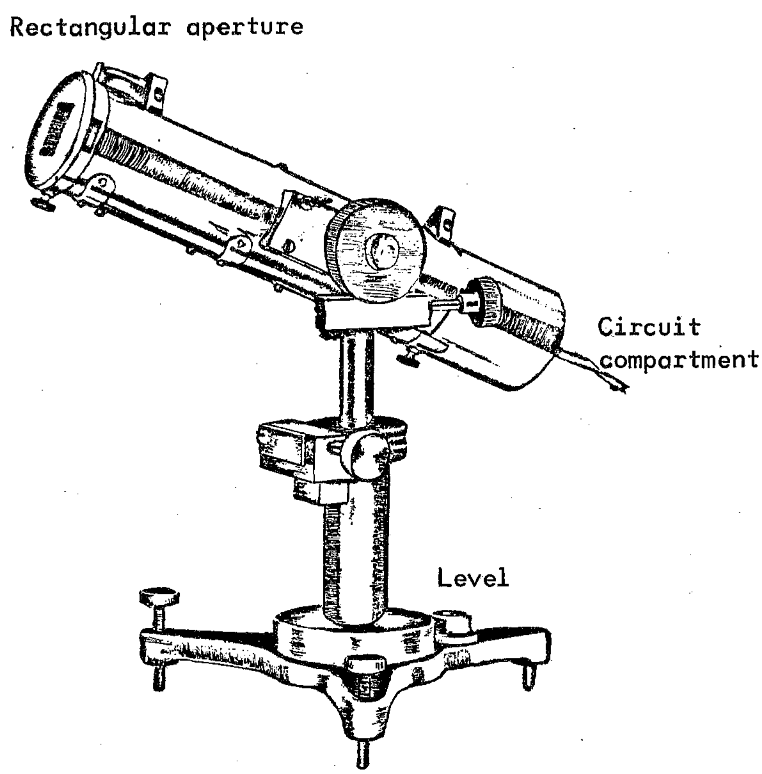


Figure 109 - Angstrom electrical compensation pyrheliometer (Eppley)

A particular design of the instrument consists of a cylindrical metal tube about 23 cm in length (including the circuit compartment), diaphragmed inside in a way to make possible the exposure to the Sun's radiation of two identical manganin strips 20.0 x 2.0 x 0.02 mm.

The rectangular aperture of each of the two radiation receivers has plane angles of 4.2° and 10.6°. The tube is equipped with sights and azimuth and elevation adjustments.

The manganin strips are parts of two electrical circuits, which may be easily switched on and off to an electrical source by the switches I and J (Figure 110). The strips are blackened with Parson's optical black lacquer. On the undersurface of the strips (denoted S_L and S_R in Figure 110), two copper-constantan thermocouples T_L and T_R are attached in series and in good thermal contact with - but electrically insulated from - the strips. The thermocouples are connected to a galvanometer by copper terminals.

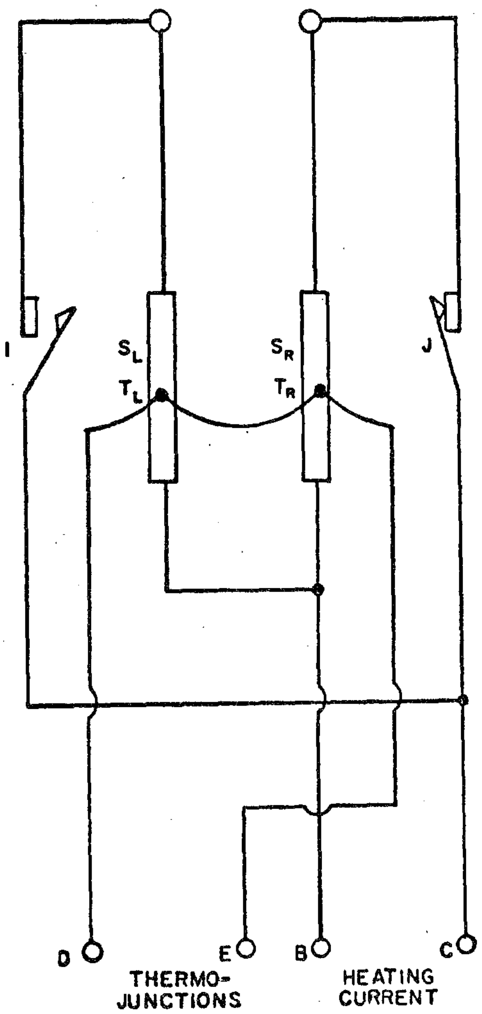


Figure 110 - Circuit diagram of Ångström pyrheliometer

At the front of the tube a small shutter is provided to enable one or other of the strips to be screened from the Sun. The shutter mechanism actuates the gold-plated contact micro-switch (I or J), thus automatically passing heating current to the shaded strip. Through a control on the heating current, it is possible to bring both irradiated and shaded strips to the same temperature, an indication of the temperature equilibrium being obtained from the thermocouple and galvonometer arrangement.

The measurement of solar radiation with the instrument is based on the following theory:

Let I be the radiation in watts per square metre, b the width of the strips in centimetres, a the absorption coefficient of their blackened surfaces (taken as 0.985 for the Parson's black), r the resistance in ohms per centimetre of the strips and i the electrical current in amperes used for compensation of the irradiated strip. The electrical heat equivalent (J) is 4.187 watts. We then have:

$$b.a.i = r.i^2 \qquad (1)$$

from which

$$I = \frac{r.i^2}{b.a} \quad (\mathrm{W\ m^{-2}}) \qquad (2)$$

In order to measure the radiation, we have to determine b, a and r.

$$\frac{r}{b.a} = k \qquad (3)$$

where k is constant, called constant of the pyrheliometer. From a knowledge of this constant and through a measurement of the compensation current, we may obtain the required radiation intensity from the equation

$$I = k.i^2 \qquad (4)$$

As the strips are exposed to the air in virtually the same manner and as they are at the same temperature, corrections for cooling and convection are thus eliminated.

It is customary to determine the constant k by a relative comparison with a primary standard pyrheliometer.

The read-out system consists of a high-precision ammeter (with the Eppley new model a digital 4 1/2 digit, ± 0.05 per cent accuracy ammeter) and a null galvanometer.

The measurement accuracy of the instrument can be affected by parasitic magnetic fields.

The silver-disk pyrheliometer, developed by Abbot, is an instrument for the measurement of direct solar radiation (Figure 111). Essentially, it consists of a metal tube provided inside with a number of diaphragms allowing solar radiation to fall on a blackened silver disk at normal incidence. The aperture of the instrument is 5.7°. A shutter enables the disk to be exposed to radiation for desired intervals of time. A bent, mercury-in-glass, high-accuracy thermometer is used to measure the temperature of the disk, its bulb being placed in a mercury-filled cavity in the disk (for a better thermal contact). A thin steel jacket coating the cavity prevents the silver from being affected by the mercury (building of amalgams) and at the same time permits a good heat transfer from disk to thermometer bulb. The silver disk is supported inside the copper tube by fine steel wires, thus making the heat exchange between disk and copper case as small as possible. The copper case itself is placed inside a wooden box in order to reduce sudden temperature changes arising from insulation or other reasons. The principle of operation of the instrument is that the initial rate at which the silver disk is heated by the Sun is found by measuring the rate of change of the disk temperature.

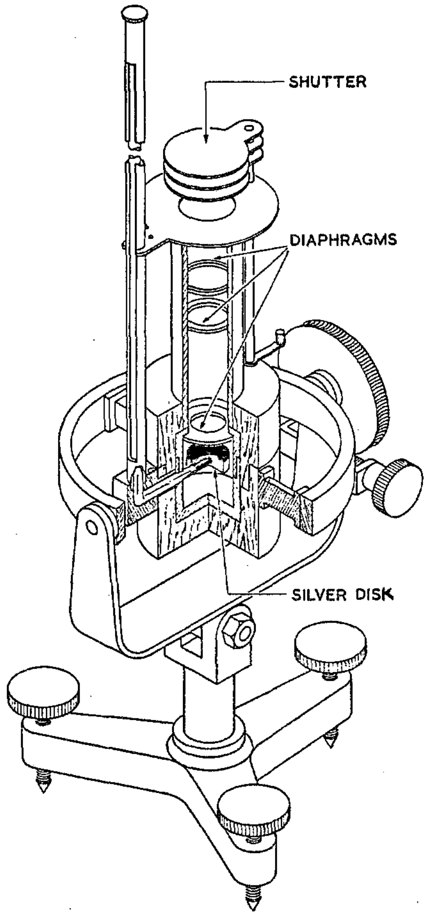


Figure 111 - Silver-disk pyrheliometer

The measurement is based on the following theory:

Let us suppose the area of the disk is A, its thermal capacity C, its instantaneous temperature is T, while the radiation intensity is I. Suppose further, that the copper-case temperature is T_c. Then the rate of loss of heat from the disk is proportional to the temperature difference $k(T - T_c)$ and the temperature of the disk will change with time according to:

$$C \frac{dT}{dt} = I.A - k(T - T_c) \qquad (1)$$

An expression for the intensity of the solar radiation is obtained in the form (after integration of equation (1) and rearrangement:

$$I = \frac{C}{A.t_1} (T_1 - T_o) \qquad (2)$$

where:

t_1 = time interval sufficiently small (t_1 much less than C/k);

T_1 = temperature of disk after time t_1;

T_o = initial value of the temperature (before the beginning of the exposure of the disk to the solar radiation.

The measurement procedures could be summarized as follows:

(1) Set the instrument up with the shutter closed;

(2) Take thermometer readings: (a) and (b), 20 and 120 s after commencement of observation;

(3) Open the shutter immediately after the reading (b), check the adjustment of the instrument and take readings: (c) and (d), 20 and 120 s after the beginning of the third minute;

(4) Close the shutter after reading (d) and take readings (e) and (f) after further periods of 20 and 120 s respectively;

(5) Repeat cycles (3) and (4), observing strictly the time intervals of observation (an error of one second may lead to an error of one per cent in the final results!).

The rate of rise of temperature, R_i, is taken as (i = index)

$$R_1 = (d) - (c) + \frac{(a) - (b) + (e) - (f)}{2}$$

$$R_2 = (h) - (g) + \frac{(e) - (f) + (i) - (j)}{2} \qquad \text{etc.}$$

Corrections must be applied to R_i (i = 1,2) as follows:

(a) The thermal capacity of the disk will vary with temperature. In order to correct for this, add $k'((T) - 30)R$ to the value of R_i, where T is the mean temperature of the disk during the exposure and k' is a constant supplied with the instrument;

(b) If the ambient temperature differs from 20°C, a correction must be applied for the effect of exposure of the thermometer's stem; subtract $k''(T_a - 20)R$ from the value of R_i. The constant k'' = 0.00014 and the entity T_a is the ambient temperature.

Applying corrections (a) and (b) reduces the observations to standard-disk and thermometer-stem temperature.

The intensity of radiation is then given by:

$$I = B.R(1 + k'(T - 30) - k''(T_a - 20)) \qquad (3)$$

where:

$k'(T - 30)$ is a correction for the disk thermal capacity;
$k''(T_a - 20)$ is a correction for ambient temperature;
B is an instrumental constant.

On account of its high reliability over long periods of time the silver disk pyrheliometer is used in the U.S.A. as a working standard pyrheliometer for calibrating secondary instruments.

The <u>Michelson bimetallic pyrheliometer</u> is a relative, secondary instrument for measuring direct solar radiation. Originally designed by Michelson (1908), the instrument was modified later by Marten and Buttner (1930). (See Figure 112.)

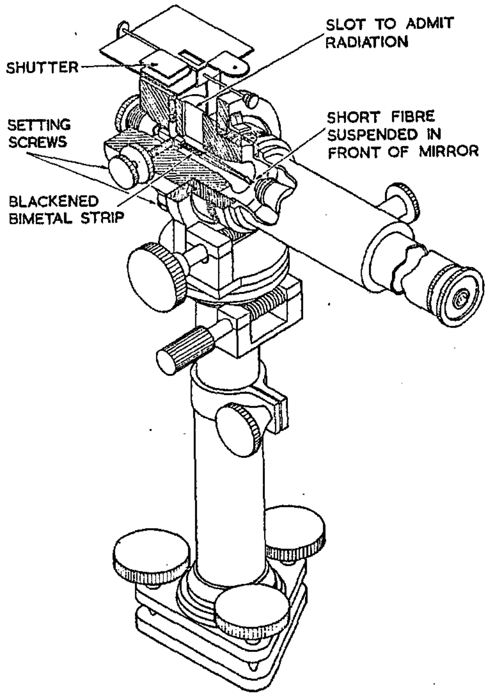


Figure 112 - Michelson pyrheliometer

In principle, the deflection of a very thin bimetallic strip (constantan-invar) painted with lampblack, irradiated by the solar beam through an aperture subtending angles approximately 10° and 25°, is a measure of the intensity of the radiation. The instrument is provided with an azimuth and elevation adjustment, enabling a normal incidence exposure of the strip to be attained with precision. A sighting device is used for that purpose as well.

The very small deflection of the bimetallic strip is observed through a microscope, having a x 60 magnification. In order to permit a more accurate reading, a short, fine quartz fibre is attached to the free end of the strip, which is visible against a scale. Both scale and quartz fibre are illuminated by a side glass-window in the body of the instrument.

The position of the free end of the strip depends on the ambient temperature as well. In the original version of the instrument a pair of setting screws were provided for the zero adjustment of the strip. In later models, temperature compensation is provided against the effect of the ambient temperature, thus eliminating the difficulties connected with the drift of the zero.

In a typical instrument, a temperature rise of the strip of about $3^{\circ}C$ indicates a radiation intensity of about 698 W m^{-2}. A full response of the sensor to a step-like change of the radiation is obtained in about 30 s. In the measurement procedures it is advisable to wait a little longer after each opening and closure of the shutter. Variations in the response time of the instrument are introduced by the effect of wind (improved ventilation of the sensor). Some models are provided with a quartz glass window to protect the radiation admittance slot. A correction for the radiation lost through reflection from the window must be made in the readings of such instruments in order to obtain the proper values of radiation intensity.

Radiation measurements in restricted portions of the spectrum can be made with the Michelson pyrheliometer, provided the instrument is designed to work with interchangeable filters.

The following observation procedures are recommended:

(1) Set the instrument on its stand, level and orient it using the spirit-level and the sighting device, in such a way that the solar radiation will fall perpendicularly on the bimetallic strip when the shutter is opened;

(2) Adjust the position of the indicating end of the strip to a conveniently low reading with the shutter closed and after the instrument has adapted to the ambient temperature. Note the reading a_1;

(3) Check the orientation of the instrument using the sight, open the shutter and wait about 45 s before taking the reading b_1;

(4) Close the shutter, wait about 45 s and take the reading a_2;

(5) Repeat observations (3) and (4) twice, thus obtaining b_2, b_3 with radiation (shutter opened) and a_3, a_4 with the shutter closed (zero position of the sensor);

(6) Find the mean bitmetallic strip deflection using the formula:

$$D_m = \frac{1}{3}\left(b_1 + b_2 + b_3 - \left(a_2 + a_3 + \frac{a_1 + a_4}{2}\right)\right);$$

(7) Using the calibration factor of the instrument, find the radiation intensity from D_m.

The Michelson pyrheliometer is a self-contained instrument of reliable calibration characteristics. Because of this and its portability the instrument is used for routine measurements of direct solar radiation, as well as a travelling secondary instrument. A measurement accuracy of better than one per cent can be obtained with an instrument checked against the primary standard, provided a series of 10-15 readings of the intensity are made (based on the shutter-open, shutter-closed scale differences).

Used as a travelling working standard, the Michelson pyrheliometer should be subjected to regular checks against a standard pyrheliometer, usually before and after transport to the field station.

The <u>Linke-Fuessner pyrheliometer</u> uses an eighteen-junction thermopile with an electrical resistance of about 30 Ω and a sensitivity of about 10mV per 698 W m^{-2} normally incident radiation. The thermopile is armoured by a thick shell of copper having a specially designed conical aperture of about 11° (Figure 113). The heavy mass of the shell prevents air currents from affecting the sensor and minimizes the temperature rise from direct solar radiation heating, as well as equalizing the temperature in the vicinity of the thermopile.

The blackening of the thermopile battery is virtually non-selective for radiation of terrestrial as well as of solar origin.

The new models of the instrument have an ambient temperature-compensating thermocouple connected in opposition to the sensing one but otherwise shaded from the solar radiation. The compensating device also eliminates thermal effects connected with quasi-adiabatic pressure changes near the thermopile, due to gusty winds.

A filter carrier mounted in the head of the instrument makes the instrument suitable for measurement of radiation emissions from the ground or specific zones from the sky.

The full response of contemporary Linke-Fuessner pyrheliometer models is about ten seconds.

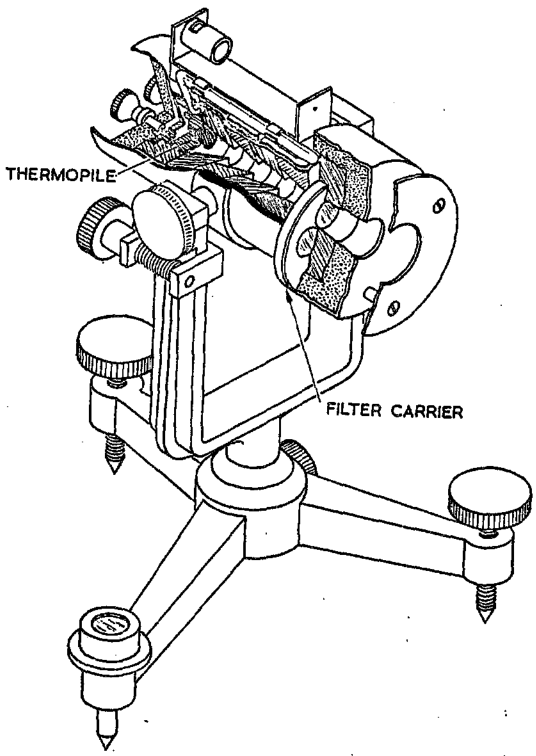


Figure 113 - Linke-Fuessner pyrheliometer

Filters are conveniently used for the separation of well-defined bands of the radiant energy of the Sun. The specific filters recommended for use internationally are the numbers OG1, RG2 and RG8, manufactured by Schott (Mainz, Federal Republic of Germany).

As there are small differences between individual filters of the same type, they are tested and certified by the Davos Observatory (Switzerland). By means of the reduction factor, DR, the measurement taken with the filters can be reduced to the intensity which would be measured by an ideal filter with a 100 per cent transmission between

- 525 and 2 800 μm for OG1;
- 630 and 2 800 μm for RG2;
- 710 and 1 700 μm for RG8;
- 350 and 2 800 μm for colourless glass;
- 250 and 4 000 μm for quartz.

The reduction factor, DR, is valid for measurements taken without a window. (For further details on filters, see IGY Instruction Manual, Part VI.)

The Yanishevsky pyrheliometer is a pyrheliometer based on a thermoelectric principle with a star-shaped thermopile and a sensitivity of about 0.1 mV per mW cm^{-2}. The aperture of the instrument is about 10° and its time for full response is about 30 s.

The Moll-Gorczynsky pyrheliometer is a thermoelectric instrument using a manganin-constantan thermopile, in limited use at present. The indicating device is a needle millivoltmeter.

(The theory of matching an electrical generator to the external circuit in order to obtain maximum transfer of energy is discussed in Part 3 of this compendium. The practical conclusions applicable to the thermopile - moving coil indicator assembly - may be summarized as follows: optimum sensitivity of the sensor-indicator system is obtained by matching their respective internal electrical resistances.)

Some of the pyrheliometers described (Ångstrom, Silver disk) are suitable only for spot measurements of the direct solar radiation. Others (any thermopile-sensor instrument) can be used for a continous recording of the radiation if the signal is fed into the input of a recording instrument (usually an electronic potentiometer) and the pyrheliometer itself is trained on the solar disk throughout the day.

Auxiliary equipment to track the solar disk during its traversal of the sky is known as an equatorial mount (Figure 114). The device is either electrically driven or spring-motor driven. Through a gear reduction device the rotation of the shaft to which the pyrheliometer is attached revolves at a constant speed following the motion of the Sun. The axis of rotation is perpendicular to the plane of the celestial equator. The axis needs to be adjusted daily as the Sun's declination changes.

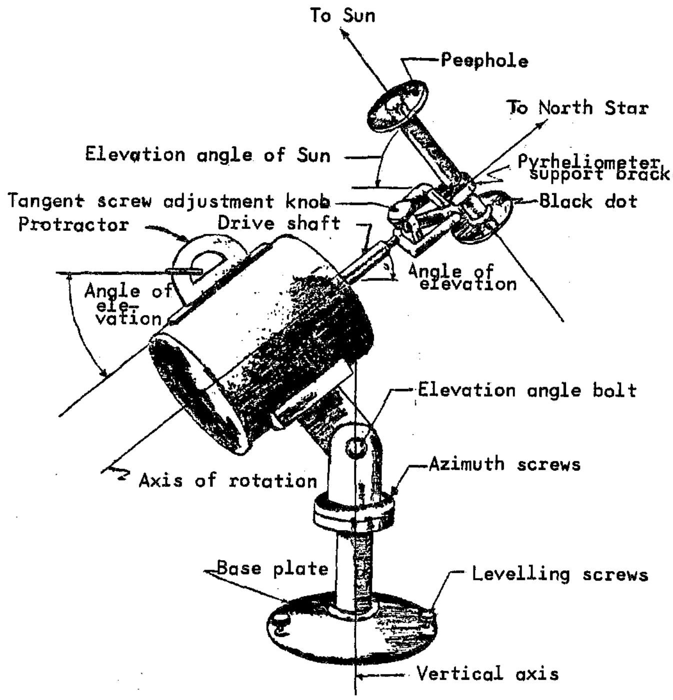


Figure 114 - Equatorial mount and pyrheliometer

Observations with the use of an equatorial mount need continuous supervision from well-qualified personnel. Equatorial mounts driven by electrical synchronous motors, which depend on the stability of the mains frequency, tend to drift out of synchronization with the motion of the Sun.

Care should be taken that the pyrheliometer's cables do not get twisted by the equatorial mount's motion, thus loading the driving shaft additionally and eventually causing damage to the pyrheliometer itself.

The sensitive element of the Eppley normal-incidence pyrheliometer for either total or spectral measurement of direct solar radiation is an eight-junction thermopile (copper-constantan) with a circular receiver of about 5.5 mm diameter, coated with lampblack (Figure 115). In effect, the instrument could be considered a thermoelectric version of the silver-disk pyrheliometer, as it incorporates in its design some of the basic features of that instrument.

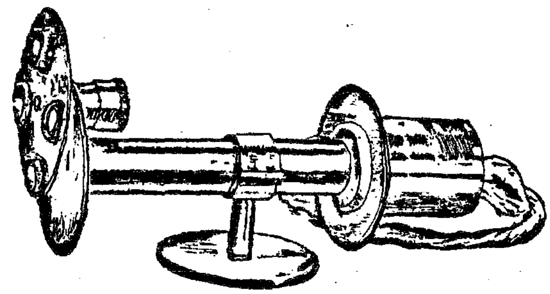


Figure 115 - Eppley normal incidence pyrheliometer

The thermopile heat-sink is provided with a temperature-compensating thermistor. The temperature dependency is ± one per cent over an ambient temperature range of -20° to 40°C.

The thermopile is mounted in the base of the brass tube, the aperture of which bears a ratio to its length of 1:10, subtending an angle of 5°43'30''. The inside of the tube is provided with suitable diaphragms and is painted black. The instrument is chromium plated on the outside. The tube is filled with dry air at atmospheric pressure and sealed at the viewing end by a crystal quartz insert one millimetre thick, which can be removed if necessary.

A sighting arrangement and a manually rotatable filter disk are available. The rotatable disk accommodates three filters (OG1, RG2, RG8) and one free aperture for total spectrum measurements.

The sensitivity of the pile is 4 - 7 mV per 698 W m^{-2} and its impedance about 200 ohm. The 1/e response time is one second and linearity is preserved up to 2 791 W m^{-2}.

The instrument can be used for periodic measurements, as well as for continuous records of radiation. The latter alternative could be realized through the use of an equatorial mount and a recorder.

9.2.2 Total (global) solar-radiation measuring instruments

Measurement of the total radiation of Sun and sky is most useful and is generally taken over a unit area of a horizontal surface and integrated over a period of time. This quantity is subject to wide and rapid variations and instantaneous values are often unrepresentative. Recording and integration of the total radiation are aspects of the measurement of this radiation component.

The principal instrument for measuring total radiation is the pyranometer. It is generally an all-weather instrument permanently installed at the observing site. The sensor is protected by a glass dome and because the performance of the instrument depends very much on the condition of the envelope, measurements with a pyranometer require frequent inspections (at least once a day).

Two versions of the Eppley pyranometer are available: the sixteen-junction and the fifty-junction Eppley 180° pyranometer. The thermojunctions are made of gold-palladium and platinum-rhodium alloys respectively. In each instrument, the hot junctions are in good thermal, but not electrical, contact with the inner concentric silver ring, blackened with Parson's black. The cold junctions are in good thermal, but not electrical, contact with the outer concentric silver ring, coated white with magnesium oxide. The total diameter of the receiving surface is 29 mm. The central supporting disk is flush with the sensor and similarly whitened (Figure 116).

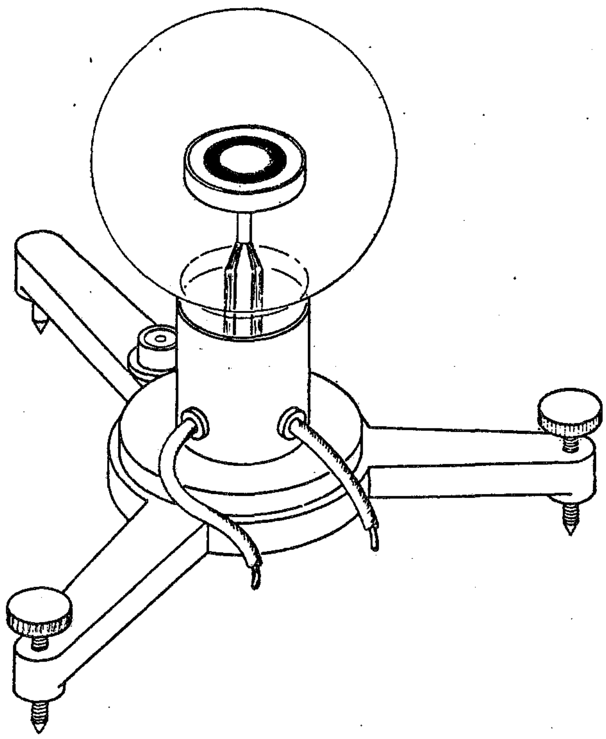


Figure 118 - Eppley 180° pyranometer

The concentric ring assembly is hermetically sealed in an optical soda-lime glass bulb 75 mm in diamter. The protective bulb is filled with dry air.

Both the white and black receivers are similar in their absorption properties as far as long-wave radiation is concerned, and this minimizes the effect of the long-wave radiation of the glass envelope. As regards short-wave solar radiation, the white ring possesses a high reflectivity, while the black one has a high absorption. This leads to a good voltage response when exposed to solar radiation, which is linear within the measuring range.

The sensitivity of the ten-junction model is about 2.0 mV per 698 W m^{-2} (resistance about 30 - 40 Ω); the fifty-junction model has a sensitivity of about 7 - 8 mV per 698 W m^{-2} and a resistance of about 100 Ω . The time for a 99 per cent response of the pyranometer is about 30 s and its temperature dependency lies within the range of -0.06 to -0.12 per cent per degree Celsius.

For continuous records of the total solar radiation with the Eppley 180° pyranometer an electronic potentiometer (Speedomax W or alternative) is used.

The totals of the solar radiation can be obtained through an integrator (the Leeds and Northrup Disk Integrator Series 300 or similar).

The sensor of the Moll-Gorczynsky pyranometer consists of fourteen manganin-constantan thermojunctions arranged in the form of a rectangle, approximately 14 x 10 mm (Figure 117). The hot junctions run along a line in the middle of the receiving surface, which is painted black. The cold junctions are in good thermal, but not electrical, contact with the heavy brass case of the instrument. The rectangular receiving surface is mounted flush with the metal casing, which is chromium-plated on the outside. The sensor is protected from the weather by a double glass dome, each hemisphere being 2 mm in thickness and with external diameters of 30 and 50 mm respectively. The spheres are sealed in grooves set into the upper surface of the instrument.

Provision is made for the attachment of a desiccator, and a screening disk to prevent radiation from affecting the junctions from below.

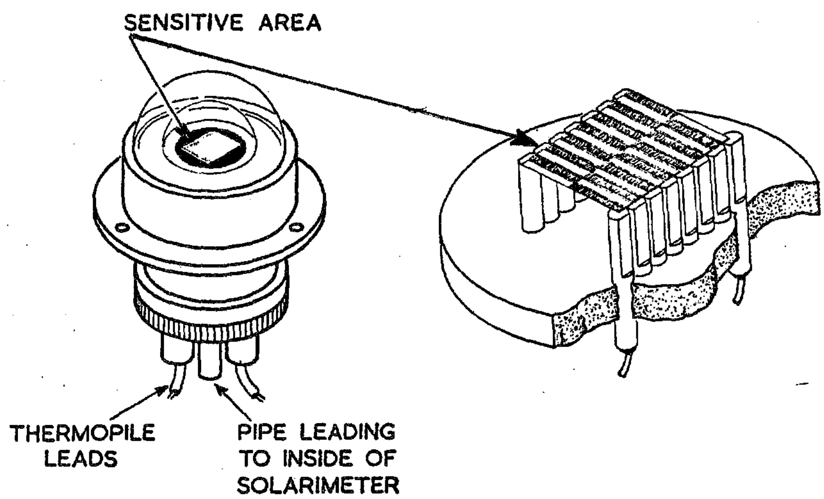


Figure 117 – Sensitive area of Moll-Gorczinski solarimeter

The sensitivity of the sensor is 7 - 8 mV per 698 W m^{-2} and the resistance approximately 10 Ω .

The 99 per cent response time is about 15 s.

A negative temperature coefficient is reported by some authors amounting to -0.1 per cent per degree Celsius.

A model manufactured by Kipp and Zonen, known as the CM-6 solarimeter, has the following characteristics: transmission range of glass domes - 300 nm to 2.5 μm; sensitivity about 8 mV per 698 W m^{-2} (115 mV per W cm^{-2}), internal resistance about 10 Ω , accuracy better than one per cent, linearity better than one per cent over the whole range; temperature coefficient -0.15 per cent per degree Celsius, 99 per cent response time about ten seconds. The CM-6 solarimeter is used with the CC-1 or CC-2 integrator and BD 7/8 electronic recording potentiometer.

The Yanishevsky pyranometer is a thermoelectric instrument using hot and cold thermojunctions painted respectively black (soot) and white (magnesium oxide). The sensor measuring 3 mm x 3 mm is protected by a glass dome and provided with a desiccator (silica gel).

The sensitivity of the instrument is about 0.1 mV per mW cm^{-2} (10 W m^{-2}) and the 99 per cent time response about 30 s.

The totals of solar radiation can be obtained through an integrator. One simple form of integration is based on the mechanical rotating ball-and-disk principle (Disk integrator, Series 300, Leeds and Northrup (Figure 118). This integrator is an attachment to the potentiometric recorder Speedomax W).

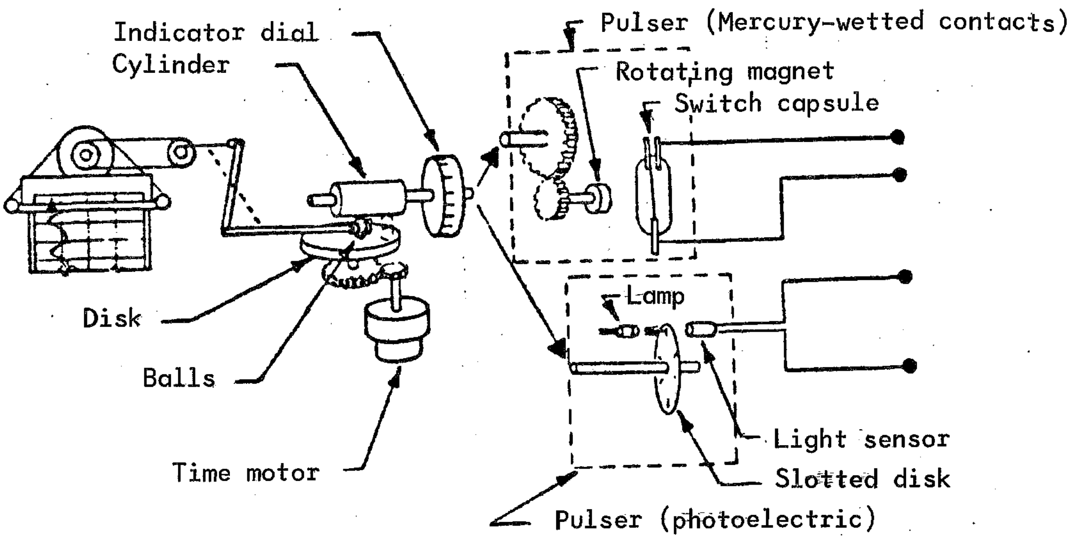


Figure 118 - Diagram of an electromechanical integrator (Series 300)

A ball positioned on a flat, rotating disk will turn at a speed proportional to its distance from the centre of the disk. The disk that drives the ball is turned at a constant speed by an a.c. motor. The ball is moved across the disk by a mechanical connexion whenever the recorder indicator moves from its baseline. The rotating ball drives a roller-shaft, which is coupled to a pulser. The pulser amplifies the rotation through a step-up gear train, which in turn rotates a permanent magnet in front of a reed-switch. The end result is a continuous series of electric pulses proportional to the ordinate of the recorded variable (the position of the recorder indicator above the baseline). The pulse output is used to advance an electromechanical counter or digital printer, which provides a summation of the pulses over a selected period of time. After reading the total radiation the integrator is re-set and the integration continues for the next period of time.

An alternative design of the pulser is based on a photoelectric principle (Figure 118). Instead of a permanent magnet a light-chopper disk is rotated chopping the light falling on a photodiode from a small electric bulb. The pulse train is processed in much the same way as above.

The accuracy attained through the disk integrator is ± 0.1 per cent of full-scale deflection or ± 1 count, whichever is greater. The linearity is 0.1 per cent of full-scale deflection (F.S.D.) and the maximum output is 1 200 p.p.m.

The integrator could be used with the Eppley 180° pyranometer.

An electrical version of an integrator is illustrated in Figure 119. In this integrator the e.m.f. of the pyranometer is fed into the voltage amplifier of the instrument. The voltage amplification could be set by a pyranometer constant-setting device. At the output of the voltage amplifier a calibrated voltage is obtained (10 mV per 698 W m^{-2}) to be used for recording with an electronic potentiometer. Amplified voltage from the amplifier is converted into current and subsequently into pulse frequency. The pulse train is applied to the input of a pulse shaper (a monostable multivibrator) and the square pulses are counted by two electromechanical counters, switched in succession after an operational period of twelve hours (switching time 0.00 LMT). A conversion coefficient (20 counts per 41 868 J m^{-2}, for a specific model) is used in the evaluation of the count. The counters are provided with a re-set button, which is pressed on the one which is off after reading the read-out.

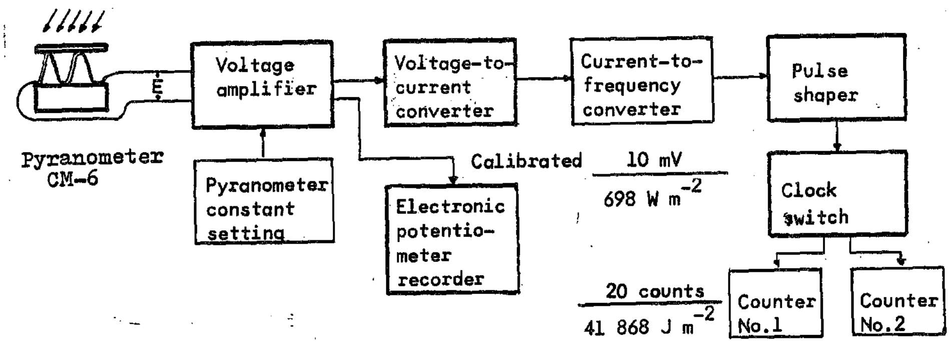


Figure 119 - Block diagram of an electronic integrator (CC-1)

The electrical integrator has better characteristics than the mechanical one and a higher reliability figure. A specific design (CC-1 Kipp and Zonen) has an input signal range of 0 - 20 mV, accuracy better than 0.5 per cent, linearity better than 0.3 per cent F.S.D., input resistance 25 Ω, false count maximum 1 count h^{-1} and a temperature coefficient of 0.1 per cent per degree.

The Robitzsch bimetallic pyranograph is designed to provide a continuous record, using either a 24-hour or seven-day clock, of the total (Sun and sky) radiation falling on a horizontal surface.

The sensor of the instrument (Figure 120 upper left-hand corner) consists of two pairs of bimetallic strips (5), one pair painted black, one white, attached to a common metal plate at one end, while the opposite ends of the white strips are fastened to the frame of the instrument and those of the blackened one are linked together to the recording mechanism of the instrument. Thus, a temperature-compensating device is obtained for the effect of the ambient temperature. The "free end" deflection of the black strips is transmitted through a magnifying lever system to the recording pen (10). Black and white strips attached to a common plate at one end, bending in opposite directions by a change of the air temperature between them, react only to a temperature difference resulting from the solar radiation. The recording is obtained on a clock-driven chart (daily or weekly) in ink.

The hermetically-sealed glass dome (1) is transparent for radiation in the wavelength range 0.36 - 2.5 nm. The white painted baffle (6) under the sensor assembly prevents extraneous light reflections from inside the case from affecting the measurement.

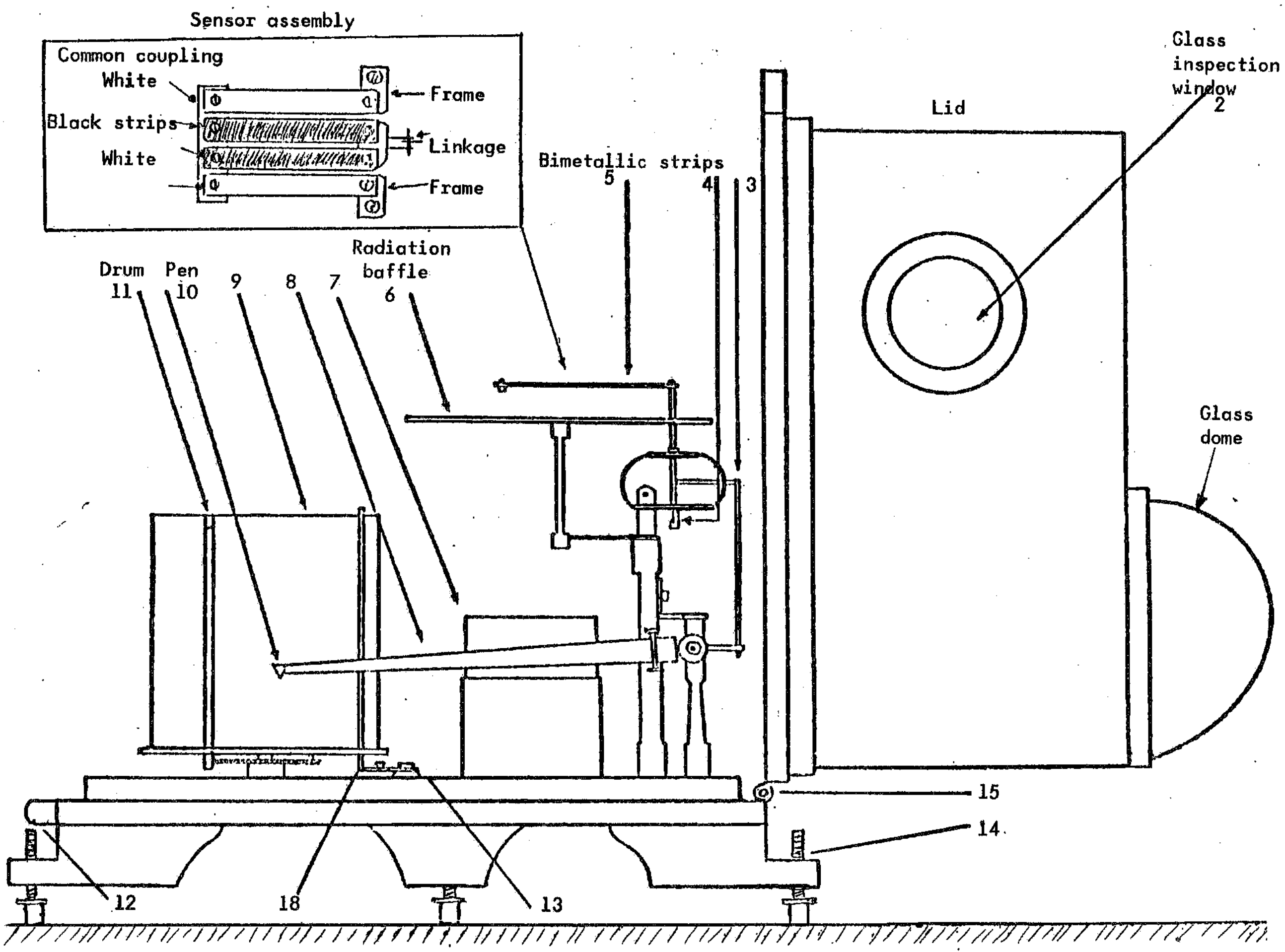


Figure 120 - Mechanical pyranograph (Robitzsch type)

Depending upon the calibration, the smallest scale division of the instrument's chart corresponds to approximately 3.5 W m^{-2}, the F.S.D. being 1 744.5 W m^{-2}.

An air- and moisture-tight case, painted white to reduce absorption of heat, covers the sensors and the recording mechanism. The case is hinged at one end to the base frame of the instrument giving full access to the chart and mechanism. A small window (2) on the front of the case permits the reading of the chart without opening the instrument. Rubber gaskets and a screw-tightened latch (12) are provided to enable the sealing of the case against the elements. Water vapour inside the case is absorbed by a desiccant in a small container (7). This prevents condensation on the sensor assembly (the black strips are more likely to be affected by condensation because they irradiate more strongly) and the glass dome. Levelling screws (14) and a spirit level are provided to facilitate the precise levelling of the instrument at the observation site.

The Robitzsch pyranograph should be installed at a place where there are no obstructions which might cast shadows or reflect radiation onto the instrument. The roofs of tall buildings could be used for such a purpose. The small observation port of the instrument should face true north.

The Robitzsch pyranograph is a robust instrument needing very little maintenance. Mechanism and sensor assembly should be kept free of dust by cleaning regularly with a soft camel-hair brush. Light instrument oil should be applied periodically to the various pivots. The glass dome should be kept clean and perfectly transparent. While servicing the instrument the pen arm should be moved away from the chart by the pen-lifting device (13).

A bag of desiccant is always kept in the container (7). The silica gel drying properties are restored by heating in an oven to about 350°C for two to three hours.

Electrical recorders used with solar-radiation measuring instruments are usually of the electronic potentiometer type because of the very low level of the signal of the thermopile instruments and the necessity for high recording accuracy.

A null-balance principle is usually employed in such recording instruments, illustrated in Figure 121.

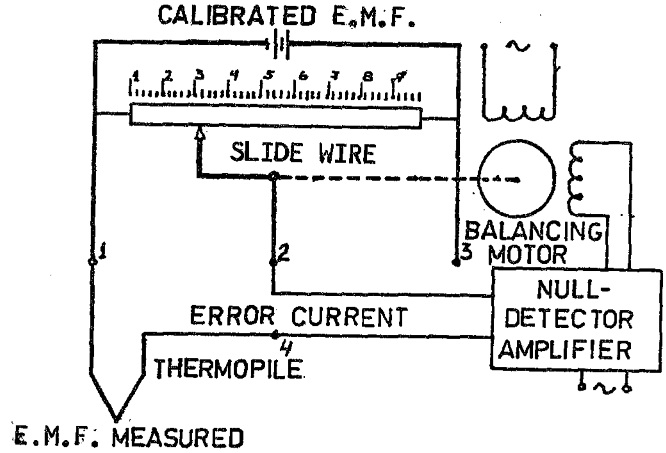


Figure 121 - Principle of a self-balanced electronic potentiometer

The measured e.m.f. obtained from the thermopile is compared with a calibrated e.m.f. through the null-balance circuit based on a slide-wire potentiometer. The process of comparison is automatic. As long as there is an error voltage between the leads (2) and (4), the reversible balance-motor - to the shaft of which is attached the potentiometer sliding contactor (and dial needle or recording pen) - turns in the required direction to make the error voltage zero. The error voltage is the difference between the measured one and the calibrated one. The direction of the rotation of the motor depends on the polarity of this voltage, always sliding the potentiometer's contact to a position on the slide wire where the error voltage is zero.

The motor is actuated by the output voltage of the null-detector amplifier. The output voltage of the amplifier is the error voltage chopped at the mains frequency and amplified accordingly. Its phase depends on the error signal polarity.

The null-balance motor is powerful enough to drive the recording pen of the instrument.

Using a resistance-bridge configuration instead of a thermopile, the basic method described is also applicable for measuring resistance, or through it a non-electrical variable (temperature). In such a case the resistive sensor is connected to terminals (1) and (4), while the fourth fixed-value bridge resistor is connected between terminals (3) and (4).

Electronic potentiometer recorders use strip recording charts with feed and take-up rolls and an electric motor drive.

Modern electronic potentiometer recorders are solid-state, multi-range and variable recording speed devices with a high, k Ω , input resistance.

9.2.3 Measurement of diffuse solar radiation

For measuring or recording the diffuse (sky) radiation component, direct solar radiation must be screened and the pyranometer exposed to the sky radiation only. Either a small disk is held in the way of the direct ray through the use of a heliostat (similar in function to the equatorial mount) or a shade ring attachment, fixed in a suitable way to the pyranometer's stand.

The shade-ring attachment requires no electrical power and needs less attention from observers in comparison with the shade disk. The shadow ring (Figure 122) is attached to an arm (B) in such a way that it can slide along a polar axis and be fixed in a desired position with the help of the screw (C). The arm (B) pointing to the North Star in the northern hemisphere has an inclination to the horizon equal to the geographical latitude of the site.

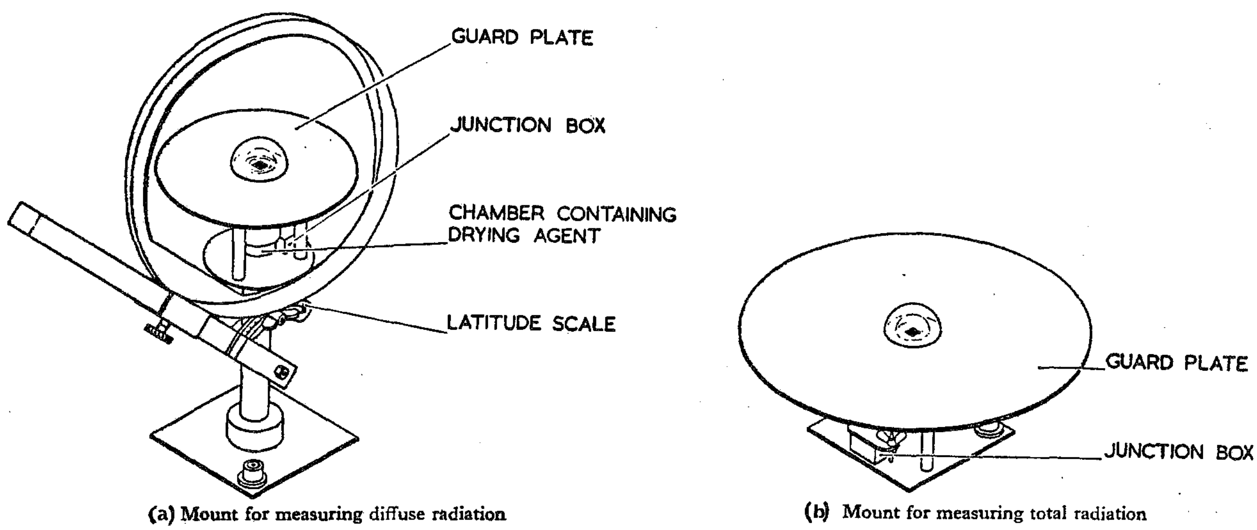


Figure 122 - Shading-ring attachment

Two kinds of adjustment are necessary for the proper operation of the shade ring:

(a) Levelling, azimuth and latitude angle adjustments;

(b) Adjustment for the Sun's declination.

The first adjustment is made at the installation of the attachment. The second is made daily so as to keep the sensor shaded, with the changing declination of the Sun.

The shade-ring width is about the same as the glass hemisphere of the shaded pyranometer (about 50 mm). On the inside it should be painted black in order to prevent reflected radiation reaching the sensor.

A small amount of the sky circumsolar radiation is lost because of the shade-ring attachment. A correction must be introduced for this purpose (see IGY Instruction Manual, Part VI, page 428 and the Guide to Meteorological Instruments and Methods of Observation (WMO-No. 8)).

9.3 Siting and exposure of solar-radiation measuring instruments

In selecting a location for a new solar radiation station, a few considerations must be taken into account:

(a) The position of the new station in relation to already existing radiation stations;

(b) Proximity of any aerological station to the radiation station to be established;

(c) Availability of qualified personnel and the possibilities for uninterrupted measurements for a climatologically significant time period.

The following requirements should be kept in mind in the selection of solar-radiation measuring instruments:

(a) The site should provide an uninterrupted view of the Sun from dawn to dusk all the year round;

(b) The solar-radiation instruments should be fixed firmly to a rigid support near to the installation of indoor remote-reading and/or recording instruments. A flat roof provides a suitable solar-radiation observation site;

(c) The solar radiation site should be away from sources of pollution and radiation other than solar.

With the installation of remote-reading solar-radiation instruments based on thermoelectric principles, it is recommended that screened cable with proper earthing arrangements at both ends be used.

9.4 Routine care, checking and testing of solar-radiation measuring instruments

Keeping the glass domes of pyrheliometers and pyranometers clean and perfectly transparent is essential and is part of the daily routine of observations. They should first be cleaned with a camel-hair brush, then washed and wiped.

Equatorial mounts need attendance throughout the day.

The shade-ring attachment needs adjustment for the solar declination every day.

One pyranometer can be checked against another by exposing and operating both of them side by side for a prolonged period of time under varying radiation conditions. Closely spaced readings of the instruments must be taken or, better, recording of the output signals of both of them.

Pyranometers can be calibrated indoors using an integrating sphere. The sphere, about 180 cm in diameter, is hinged to open along its equatorial plane. The interior is fitted with a rotatable table capable of accommodating three pyranometers for calibration. Six floodlights, of 150 W each, are used as the radiation source.

The lamps are underrun at about 90 per cent of their nominal voltage from a voltage source stabilized to within 0.1 per cent. Air is forced in from the top of the sphere and expelled from its lowest part, thus keeping the air temperature reasonably stable (up to 6°C temperature increase above the ambient temperature). The output signals of all three pyranometers are recorded. The air temperature inside the sphere is monitored.

Bimetallic pyranographs tend to change their calibration factors faster than electrical instruments. This is due mainly to the deterioration of the paint of the sensor and changes in its radiation-absorption coefficients through the effect of the weather. For this reason, the calibration of the instrument should be checked at least once every two years. A comparison with a thermopile instrument should be carried out during a number of cloudless days at different ambient temperatures and radiation conditions (read-out time intervals not exceeding 30 minutes). Due attention should be given during the calibration procedures to the difference in response time of calibrated and working standard instruments. Morning and afternoon observations should be equal in number.

The results of the observations should be plotted in a co-ordinate system: solar intensity according to the standard instrument, I_s, against solar intensity according to the calibrated instrument, I_r. A straight line is fitted to the plotted data; the slope of this line gives the correction coefficient for the calibrated instrument (Figure 123).

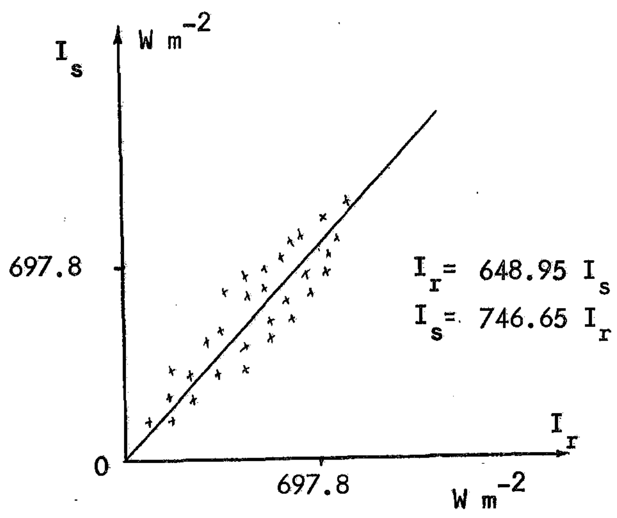


Figure 123 - I_s versus I_r plot for calibration purposes

In order to find the hourly and daily totals of solar radiation from the records of a bimetallic pyranograph the charts are planimetered, i.e. the surface area below the graph on the chart is measured through a mechanical planimeter. A reduction coefficient, A, is calculated relating the unit of chart area (one square centimetre) and the radiation amount per unit area (in joules per square metre).

If a is the radiation intensity in W m^{-2}/1 mm ordinate of the recording and M is a one-hour period of recording expressed in millimetres along the abscissa, the value of A is obtained from the relationship:

$$A = \frac{60.a}{100.M}$$

Prior to the evaluation of the chart, a correction for the time setting of the instrument might be necessary, allowing for the inaccuracy of the clockwork.

The accuracy of the bimetallic pyranograph is between 5 and 10 per cent.

C H A P T E R 10

CLOUD-BASE HEIGHT MEASUREMENT

10.1 General - units of measurement

Cloud height, especially the height of the base of low clouds, is of particular interest to aviation. Clouds are classified into three main groups, depending on the height of their base above ground:

(a) Low clouds, having a base height below 2 000 m (Stratocumulus, Stratus, Nimbostratus, Cumulus and Cumulonimbus types);

(b) Medium clouds, having their base height lying between 2 000 m and 7 000 m (Altocumulus and Altostratus types);

(c) High clouds, with bases above 7 000 m (Cirrostratus and Cirrocumulus clouds).

This classification is valid for the temperate regions. For the polar and tropical regions, cloud bases are respectively lower and higher than those indicated above.

The base of a cloud is defined in the WMO Guide to Meteorological Instruments and Methods of Observation as "the lowest zone in which the type of obscuration perceptibly changes from that corresponding to clear air or haze to that corresponding to water droplets or ice crystals. In the air below the cloud the particles causing obscuration show some spectral selectivity; in the cloud there is virtually no selectivity, the difference being due to the different droplet sizes involved". This definition of cloud base is complicated and not very suitable for practical measurements.

Cloud-base height, especially that of low clouds, is subject to considerable variations, both in space and time. Davis (1969), gives the following formula for the low cloud-height perturbation over various time intervals:

$$\sigma(t) = 110 \sqrt{1-e^{-0.218\,t}}$$

where:

$\sigma(t)$ = standard deviation of the low cloud-height perturbation;

t = time (in minutes).

Based on the model of standard deviation of the cloud-height perturbation given by Davis is the graphical presentation in Figure 124.

The variability of the low cloud-base height places rigid requirements on the sampling rate of cloud-height measurements.

Cloud-base height is measured in metres, although in some countries the unit of the foot is still in use.

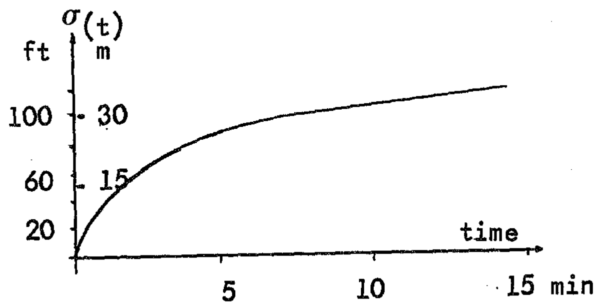


Figure 124 - Cloud-height perturbation

10.2 Principles of cloud-base height measuring instruments

10.2.1 The pilot-balloon ceiling measurement

On an assumption of a constant and known balloon ascent velocity, w, and a measured time, t, for a pilot balloon to enter the cloud base, the height of the latter can be obtained from the relationship:

$$H = w.t \text{ (H in metres for w in m s}^{-1}\text{ and t in seconds)}$$

The observation can be made either with the naked eye or using a pilot-balloon theodolite and a stop watch.

Dark-coloured pilot balloons should be used for the purpose, weighing 5 - 15 g and inflated to rise at 100 - 150 m s^{-1}. This method is suitable for night use too, in which case larger (20 - 50 g) balloons are used carrying small battery-operated electric lanterns.

Cloud-base height measurements by pilot balloon are slow and prone to errors. With rather low cloud bases, the measurement is affected by the variable speed of the balloon at the beginning of the ascent. This method cannot be used in conditions of precipitation.

10.2.2 The cloud searchlight - alidade

With this method, a narrow parallel beam of light is projected vertically or at a known angle on to the cloud and the angle of elevation of the light spot produced on the cloud base is measured by an alidade or an optical instrument from the other end of a baseline of known length.

There are three main forms of this method, which is suitable for night-time cloud-ceiling measurements.

In its simplest form (Figure 125), the searchlight beam is pointed vertically at the cloud. If the baseline length is I and the angle subtended by the light spot on the cloud base as seen from the alidade (A) is a, the following relationship is valid:

$$H = I.\tan a$$

If the searchlight is installed higher or lower than the alidade, a corresponding correction is introduced for the difference in elevation.

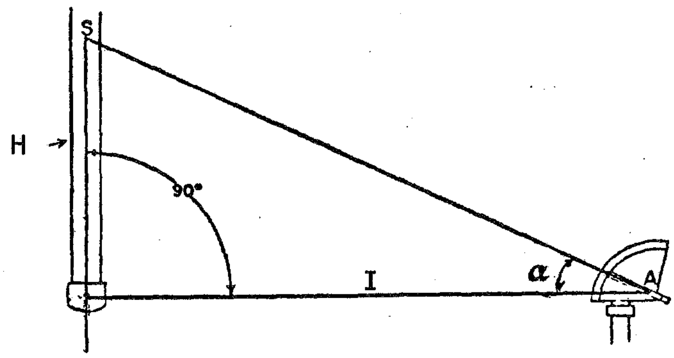


Figure 125 - Vertical-beam projector

The searchlight beam should have a spread not exceeding 2° and should be capable of illuminating cloud bases up to 3 000 m. This is possible through the use of a good-quality parabolic mirror of 40 - 60 cm diameter and a light source of 500 W (incandescant lamp, usually a low-voltage one). A searchlight for a vertical beam is shown in Figure 126. The light bulb (19) is mounted in a special bracket (4) enabling precise focusing of the bulb. Focusing is carried out at every change of the bulb, which usually has a life-span of about 100 h. The light beam has a maximum intensity greater than 10^{6} candelas.

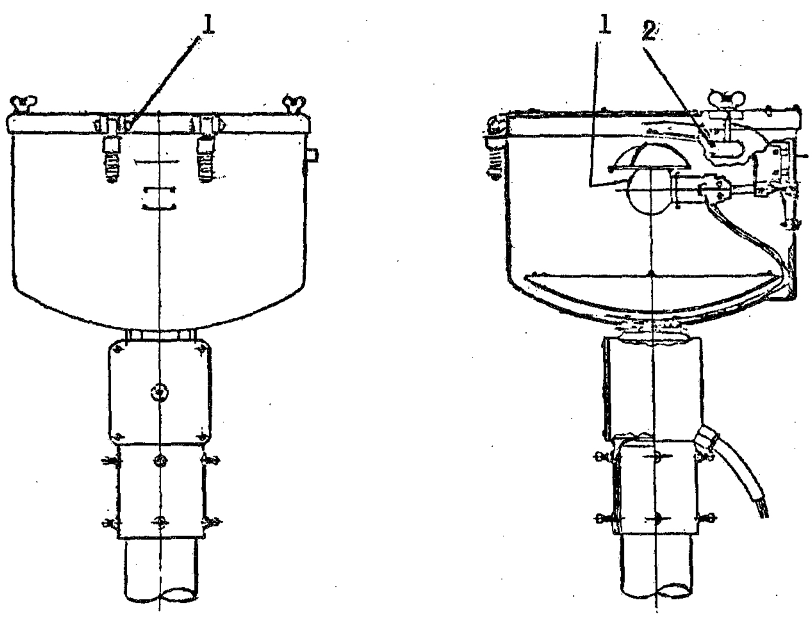


Figure 126 - Search-light of vertical-beam projector

Installation detail concerning the searchlight is given in Figure 127. As already mentioned, the light source of the projector uses a low voltage (12 V), which requires the use of a step-down transformer. The baseline is selected, depending on the available space, from 50 - 300 m.

The observation of the light spot is made with the help of an alidade (Figure 128), which is a simple sighting device having no optics, but enabling accurate reading of the elevation angle, a, of the light spot.

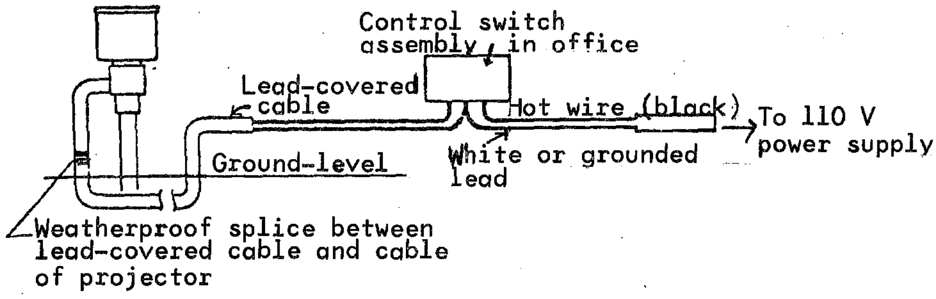


Figure 127 - Wiring diagram of a vertical-beam projector

The second alternative use of a searchlight for measuring cloud-base height is illustrated in Figure 129. The searchlight beam need not be vertical. The searchlight is supported in a U-shaped arm by trunnions and tilted at an angle of 63° 26'. The principle is again based on a trigonometric relationship, which is readily deduced from Figure 130.

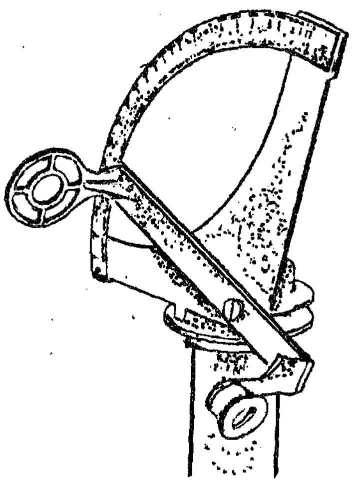


Figure 128 - Alidade

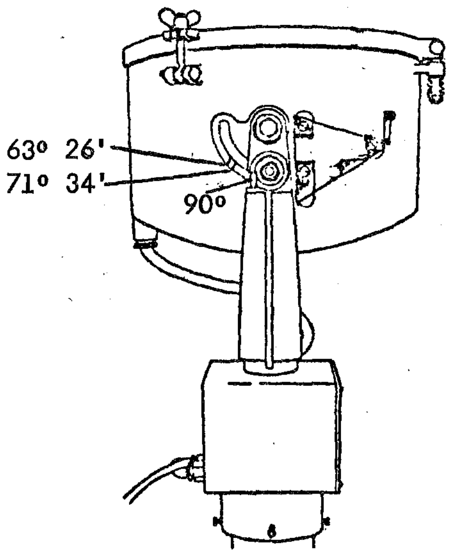


Figure 129 - Inclined-beam ceiling projector

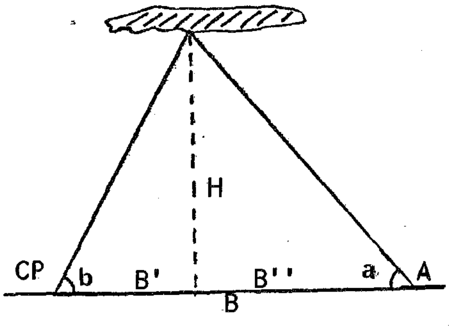


Figure 130 - Geometry of cloud-base height estimation:
CP = ceiling projector;
A = alidade;
B = baseline;
H = estimated height

If the ceiling projector and the clinometer (alidade) are installed at opposite ends of the baseline, B, and the projector beam is inclined at an angle b, while the alidade observes the light spot on the cloud-base at an angle a, the following trigonometric relationships hold:

$$B = B' + B'' \tag{1}$$

$$B'' = B - B' \tag{2}$$

$$B' = H.\cot b \tag{3}$$

$$H = B'' \tan a \tag{4}$$

therefore:

$$H = (B - B')\tan a = (B - H.\cot b)\tan a \tag{5}$$

or

$$H\ (1 + \cot b.\tan a) = B.\tan a \tag{6}$$

hence:

$$H = \frac{B.\tan a}{1 + \cot b.\ \tan a} \tag{7}$$

where:

b $= 63^{\circ}26'$;

cot b = 0.5 and equation (7) can be re-written:

$$H = \frac{2\ B.\tan a}{2 + \tan a} \tag{8}$$

The inclined-beam ceiling projector is shown in Figure 129. Its installation and operation do not differ from that of the vertical-beam device. A third alternative of using the inclined ceiling projector in measuring the cloud-base height is shown in Figure 131. Without going into a deeper discussion of this alternative, the end result could be presented in the form:

$$H = \frac{2\ B.\tan a}{\tan a - 2} \tag{9}$$

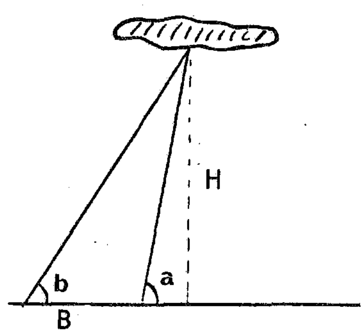


Figure 131 - Geometry of inclined-beam cloud-base estimation (see Figure 130)

The accuracy of both types of ceiling projector is good up to about 1 500 m. Above this height, an error of one degree in elevation measurement will cause the cloud-base measurement to be significantly in error.

The inclined beam is generally preferred to the vertical beam. This is because the change of height per degree variation in angle is less for the inclined beam. As the angle of elevation can only be read to the nearest degree this leads to better accuracy.

The searchlight cloud-base height measurement is more accurate than the pilot-balloon method. It has, however, one serious deficiency: in its simplest form, it can be used only at night. Modulation of the light beam and the use of a light-sensitive device for tracking the light spot, while filtering out the daylight interference can make the method applicable in daylight as well. In fact, this is the method used in contemporary ceilometers.

10.2.3 The modulated light-beam ceilograph

The modulated light-beam ceilometer (ceilograph) is a further evolution of the ceiling projector. Two versions of this instrument are in use at present:

(a) Rotating transmitter, known as the rotating beam ceilograph (RBC);

(b) Rotating receiver ceilograph (RRC).

The RBC instrument is in extensive use in North America and has a scan period of about six seconds. The RRC (which is more common in Europe) has a scan period of one minute. Both the RBC and the RRC have an operational resolution of about 30 metres.

The trigonometric relationship on which the operation of the modulated beam ceilograph is based is the same as the one already discussed in connexion with the ceiling projector:

$$H = B.\tan a$$

A graphical presentation of this relationship (Figure 132) makes the limitations of the method obvious: the measurement accuracy drops significantly with the increase of the elevation angle beyond 80°.

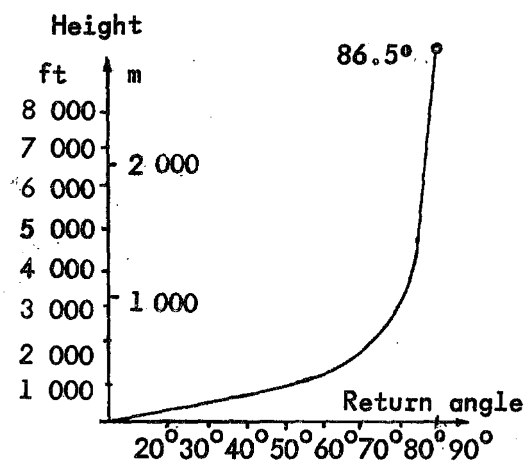


Figure 132 - Rotating receiver ceilometer (RRC) height/return-angle graph

The principle of operation of the RRC is given below. The instrument consists of three main parts: transmitter, receiver and recorder (Figures 133 and 134).

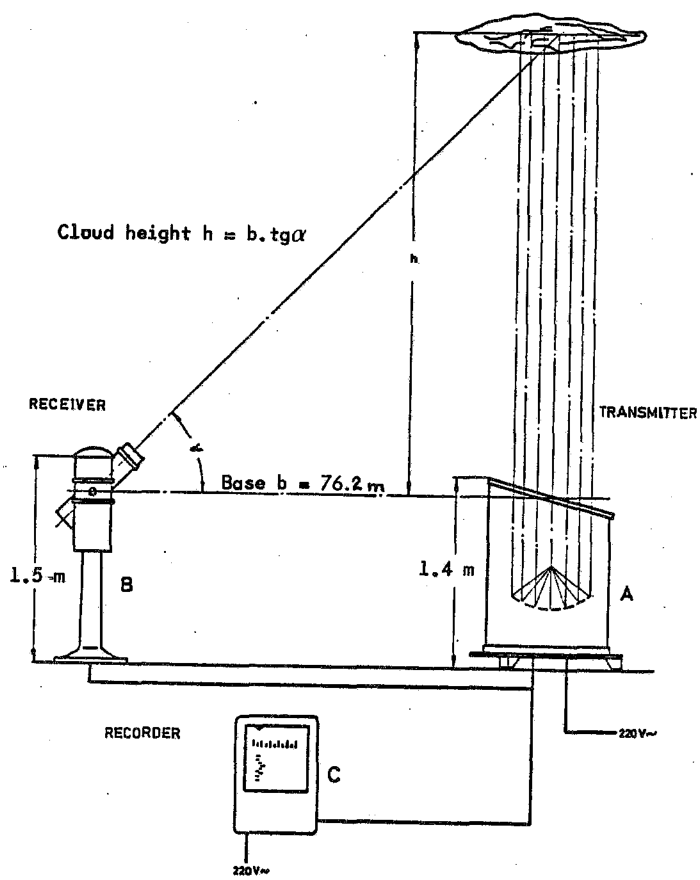


Figure 133 - Principle of the rotating receiver ceilograph (RRC)

The transmitter, using a powerful xenon lamp placed at the focus of a 520-mm parabolic mirror, emits a pulsed light beam with a very small spread (20') and of high intensity (10^8 stilb, significantly above the daylight background). The light beam, pointed vertically at the cloud base, causes a pulsing light spot to appear with an appreciable return. At the far end of the baseline (76.2 m long) is the receiver. A photocell and quartz optic housed in a metal tube scan the sky between horizon and zenith in the plane of the light beam. The scanning motion, obtained through a synchronous-motor operated crank, is slowed down as the optical tube approaches the zenith position (it stops a few degrees short of the zenith), thus compensating for the effect of the tangent function. The light pulses from the back scatter (picked up by the sensor from the light spot on the cloud base at a specific elevation angle of the tube) are converted into electrical pulses. These pulses are further amplified by a wide-band amplifier and applied to the input of a monostable multivibrator. The electrical pulses of a constant duration and amplitude obtained at the output of the multivibrator actuate the relay of the recording mechanism which is scanning the recording chart in synchronization with the rotating receiver tube. As a result, a trace is obtained on the dry electrolytic paper chart, which is moved by the transport mechanism at a constant speed of 60 mm h^{-1}. The chart is graduated in metres of height (Figure 135). The scatter of dots gives an idea of the fluctuations in the height of the cloud base.

The swinging optical tube of the receiver is provided with controlled heating. Special measures are taken to prevent background illumination from affecting the measurement. The receiver has an automatic amplification control actuated from the background illumination of the sky, thus keeping noise below a threshold value.

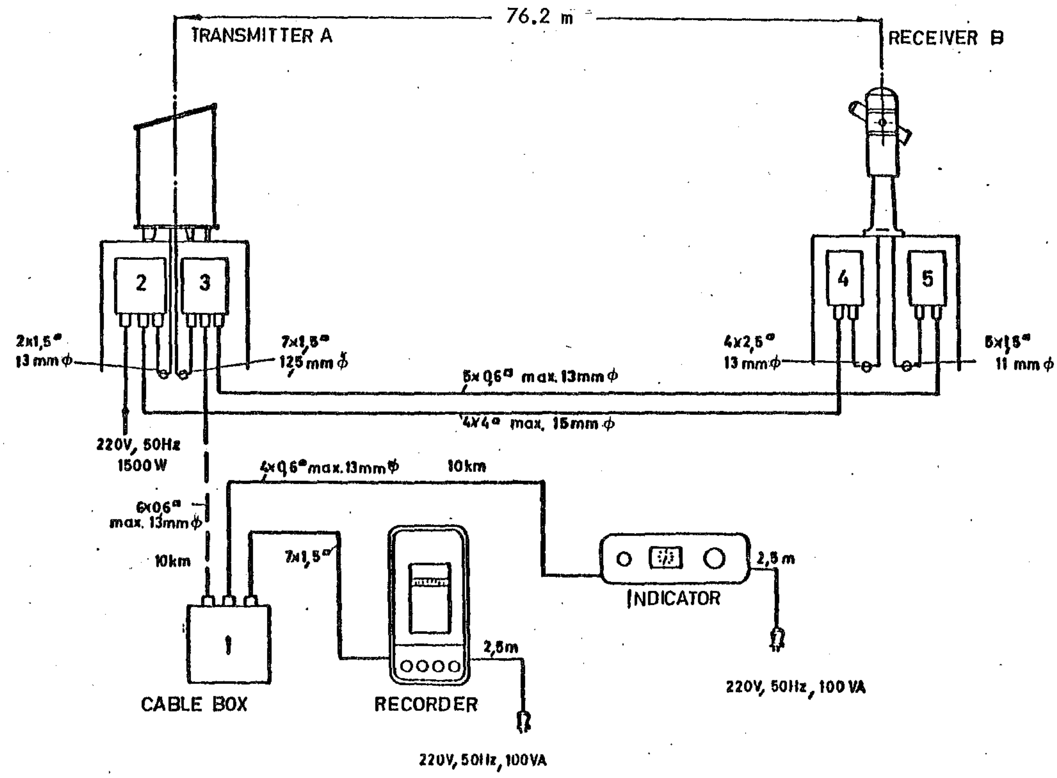


Figure 134 - Wiring diagram of rotating receiver ceilograph (RRC)

The instrument is wired using underground cable (Figure 134). The distance between the instrument and the display console can be selected within a ten-kilometre range.

The main source of error in the RBC as well as RRC instruments is optical misalignment of the system. The error of the cloud-base height measurement arising from an optical misalignment may be as much as 20 per cent.

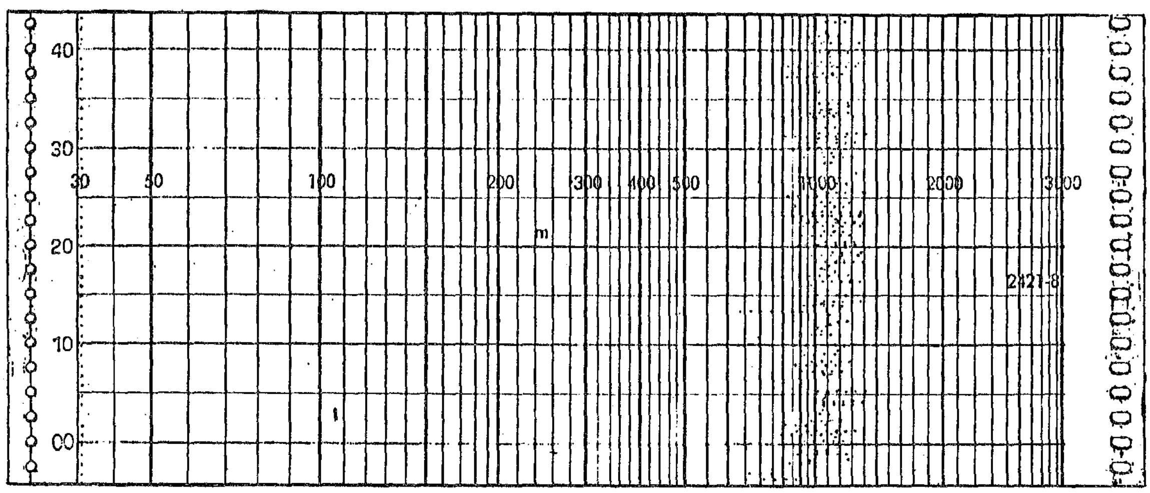


Figure 135 - Dry-electrolytic paper cloud-base recording

Routine maintenance includes cleaning of the glass cover of the transmitter and the optics of the receiver. The sensitivity of the receiver should be checked periodically.

The xenon pulse lamp has a life-span of about 300 h. At each change of the lamp it should be carefully focussed in order to retain the small spread of the light beam and its high intensity.

10.2.4 Principle of lidar cloud-base height measurement

One representative of this class of instruments is the French TNE 1500. It is an automatic ceilograph having a sampling rate of 27 soundings per hour, each one lasting about 13 s. The instrument has two ranges: 30 - 500 m and 30 - 150 m.

The cloud height is recorded on a metallized strip-chart (Figure 136) of 100 mm effective width, winding at a constant speed of 30 mm h^{-1}. The feed roll contains a recording chart sufficient for 32 days of continuous operation. The recording accuracy is $\pm$ 15 m and the smallest scale division is 100 m. The principle of operation of the instrument is illustrated in Figure 137.

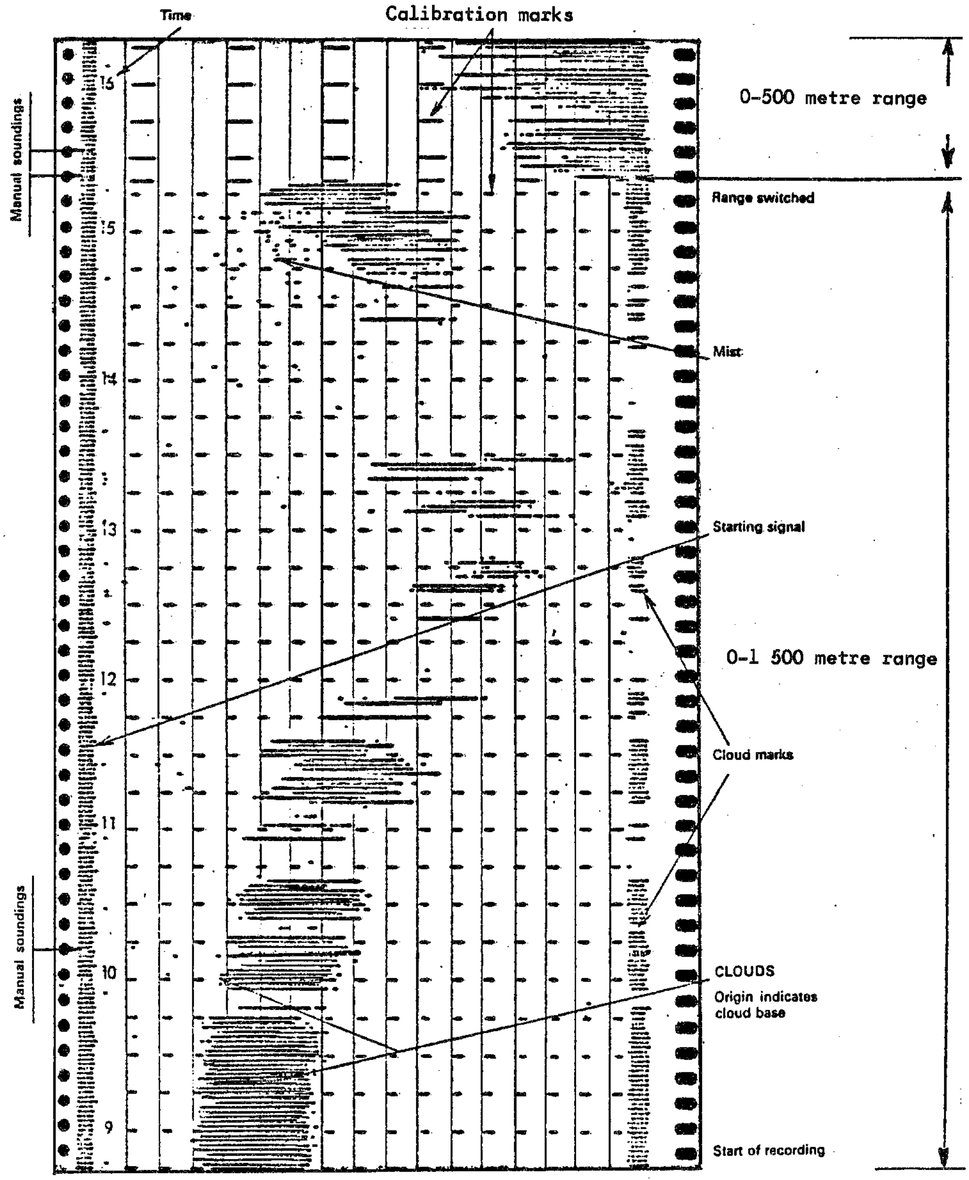


Figure 136 - Strip-chart of LIDAR cloud-base measurement

A train of high-intensity light pulses is obtained in a spark-gap between two tungsten electrodes (3) through the discharge of a 0.2 μF capacitor charged to a voltage of 7.2 kV. The pulse train is controlled by the mains frequency by an electronic stage, part of the conversion unit (13).

Through focussing of the light pulses by a parabolic mirror (5), a narrow, small-spread, high-intensity light beam is directed vertically to the cloud base.

The light pulses backscattered by the cloud droplets are picked-up by the receiver's parabolic mirror (11) and focussed on a photocell. A train of electrical pulses is obtained at the output of the photocell (10). These pulses are amplified by the electronic stages of the receiver (12). The video pulses obtained in the conversion unit (13) are compared, as far as their "excursion time" is concerned, with the scan pulses of the instrument. Coincidence of video and scan pulses result in the transmitting of a recording pulse, passed to the recorder. Thus, the cloud base height measurement by this instrument makes use of the well-known radar principle of distance-through-time measurement for the two-way excursion of the electromagnetic wave, transmitted towards the target.

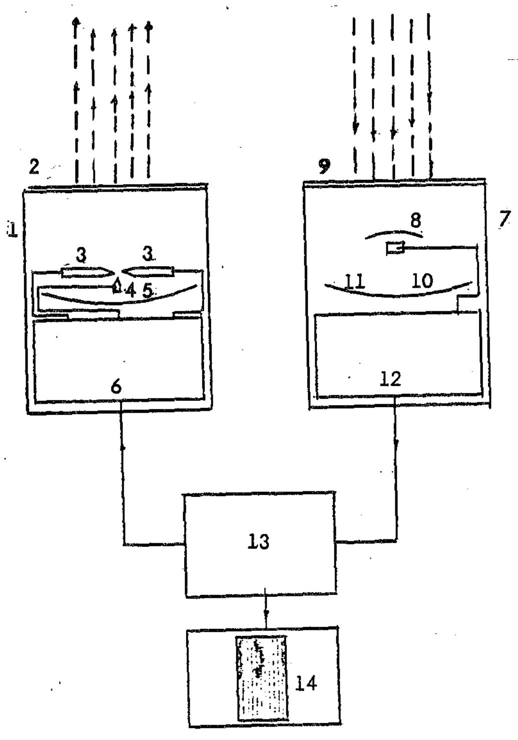


Figure 137 - Principle of LIDAR cloud-base height estimation:

(1) Transmitter;
(2) Tilted transmitter glass top;
(3) Tungsten electrodes;
(4) Exciter electrode;
(5) Transmitter parabolic mirror;
(6) Transmitter electronic unit;
(7) Receiver box;
(8) Daylight photocell protection;
(9) Receiver glass top;
(10) Photocell;
(11) Receiver parabolic mirror;
(12) Receiver electronic unit;
(13) Conversion unit;
(14) Recording unit.

The recording of the cloud-base height is made by an electrical current passed through the metallized strip-chart paper (Figure 136) either in the 30 - 500 m or 30 - 1 500 m range.

The marks on the extreme left of the chart are caused by the starting pulses of the instrument. Each one indicates the beginning of a sounding. The marks on the extreme right of the chart are obtained from clouds beyond the range of the instrument. Calibration marks coincide with the 100 m scale lines on the chart. Calibration marks of the 30 - 500 m and those of the 30 - 1 500 m range differ in length. The origin of the cloud marks indicate the cloud base. The scattered dots may be due to back scatter from mist.

The TNE 1502 is totally weatherproof. Its power consumption is about 2 kW of which 1.2 kW are used for heating the various instrument compartments.

The lidar does not need a baseline for its operation; transmitter and receiver are separated by about eight metres. This is an important advantage for installation on sites with limited space.

The lidar is an instrument of greater complexity than the RBC or RRC instruments. A modular design, however, greatly simplifies the maintenance of the electronics of the instrument and initial costs are not significantly higher.

10.2.5 Brief evaluation of common ceilometer technology

Test and evaluation of the performance of four types of cloud-base height measuring instruments – the RBC, RRC, lidar and laser – have been undertaken by the Test and Evaluation Laboratory, U.S. NWS (NOAA TM NWS T & EL- 13, 1971).

An investigation of the effect of the observation frequency on the mean ten-minute cloud-base height confirms the theoretical prediction (Duda), that an increase in observation rate beyond one per minute contributes little to the improvement of the measurement accuracy. The mean ten-minute cloud base height based on ten observations per minute differs from that based on two observations per minute by as little as 0.5 per cent.

Almost the same difference in the mean ten-minute value has been found by observations carried out by different instruments of the same type separated by a distance of about 130 m.

Based on the consideration of a number of factors pertaining to the operation of the four cloud-ceiling measuring instruments, the following ranking of the ceilometer is obtained*:

Factors	Ceilometer type			
	RRC	Lidar	RBC	Laser
Ease of installation	2	3	4	1
Maintenance	2	4	3	1
(a) Low-frequency	2	3	3	1
(b) Easy-to-perform	2	3	3	1
(c) Non-critical	1	4	3	2
Cloud-height performance	2	1	3	3
(a) In fog	3	1	4	2
(b) In precipitation	2	1	2	4
(c) In ideal conditions	1	1	1	1
Lack of noise response	2	1	3	-
(a) Strobecon	2	1	2	-
(b) Sunlight	1	1	3	-
(c) Vibration	1	1	3	-
(d) Refraction	1	1	3	-
Internal checks	2	1	3	4
(a) Included	2	1	3	3
(b) Ease of addition	1	1	3	3
Ease of automating	1	1	3	4

* 1: most agreement with statement
4: least agreement with statement

10.3 Siting of cloud-ceiling measuring instruments

For all instruments needing a baseline, an open, level and unobstructed site with the proper length would be necessary. Preference should be given to sites having a usefully oriented underground cable duct.

The light source of the ceilometer may present certain problems to aircraft operations. Special precaution should be taken with laser light sources; such instruments should be sited at a safe distance from touch-down parts of the runway.

10.4 Routine care of cloud-ceiling measuring instruments

Cleaning of the projector (transmitter) glass cover and the receiver optics should be carried out regularly with a frequency depending on the local conditions of air pollution, but not less than once a week and always after precipitation has fallen.

Control of the condition of the light source should include:

(a) State of transparency of the light bulb (with incandescent lamps);

(b) State of electrodes of the spark-gap;

(c) Check-up of the optical alignment of the instrument;

(d) Check-up of the condition of the receiver (sensitivity, noise level).

CHAPTER 11

VISIBILITY MEASUREMENTS

11.1 General - units of measurement - definition of visibility parameters

Meteorological visibility concerns the transparency of the atmosphere as related to human vision. The transparency of the air is affected by the presence of hydrometeors (rain, snow, mist, fog) or lithometeors (dust, smoke, etc.).

The following definition of meteorological visibility has been given in the Guide to Meteorological Instruments and Methods of Observation (WMO-No. 8, fifth edition): "Meteorological visibility by day is defined as the greatest distance at which a black object of suitable dimensions, situated near the ground can be seen and recognized, when observed against a background of fog, sky, etc.". Similarly, the following definition of visibility at night can be used: "Visibility at night [can be] defined as the greatest distance at which lights of moderate intensity can be seen and identified.".

A new optical parameter concerning visibility was adopted in 1957 - the meteorological optical range (MOR): "The meteorological optical range is the length of path in the atmosphere required to reduce the luminous flux in a collimated beam from an incandescent lamp at a colour temperature of 2 700 K to 0.05 of its original value, the luminous flux being evaluated by means of the photopic luminosity function of the International Commission on Illumination (CIE).".

Meteorological visibility is measured in kilometres (high visibility) or metres (low visibility) and may be indicated as visibility in a specific direction or as an average visibility.

Generally speaking, normal eyesight assumed, the day-time visibility is affected by the following factors:

(a) Presence of hydrometeors or lithometeors in the atmosphere;

(b) Direction of light (position of Sun in respect to observer);

(c) Degree of contrast between object and background.

Viewing an object against the rising or setting Sun affects the visibility estimation unfavourably.

The object viewed as a marker of visibility should be dark in colour and visible against the background of the horizon sky. It should subtend an angle of at least 0.5° in width and elevation to the observer but not more than 5° in width.

The purpose of the observation of the visibility is to provide an accurate operational estimate of the distance at which objects can be seen, to be used by pilots, seamen, etc.

Measurement of meteorological visibility can be made either visually or with the use of instruments.

With the visual estimation of visibility, the observation is made of a number of suitable objects situated at suitable distances around the station. Usually, a plan of the visibility objects is made with their bearing and distance indicated. Daylight and night-visibility objects should be distinctly marked. The observer should be provided with night-into-daylight visibility conversion tables.

Estimates of the meteorological visibility can be made in horizontal, slant or vertical direction.

11.1.1 Photometric terms and units

- Luminous flux (F) is the luminous energy per unit emitted by a light source. Unit: lumen (lm). The total luminous flux from a point source of intensity 1 candela = 4π.lm.

- Luminous intensity (I) is the luminous flux per unit sold angle: dF/dw. Unit: candela (cd).

- Candela (cd) is the unit of luminous intensity equal to 1/60 of the luminous intensity of 1 cm^2 of the surface area of a black body at temperature of solidification of platinum. 1 cd = 1 lm sr^{-1}.

- Luminance (brightness) (L) is defined as the luminous intensity per unit area of the surface of the luminous source: L = dI/dA; A is a projection of the surface of the source, normally to the line of sight. Units: 1 nit (nt) = 1 cd m^{-2}.

- Illumination (E) is the luminous flux per unit illuminated surface, S: E = dF/dS. Units: 1 lux (lx) = 1 lm m^{-2} (also 1 phot = 1 lm cm^{-2} = 10^4 lx = 10^4 lm m^{-2}).

- Extinction coefficient (σ): this coefficient is a measure of the attenuation due to both absorption and scattering.

- Transmission factor (T): this is the fraction of luminous flux which remains in the beam after traversing an optical path of a given length in the atmosphere.

11.1.2 Attenuation of light in the atmosphere

Light, or luminous energy, is radiant energy evaluated in proportion to its ability to stimulate the human sense of sight. In the sense of this definition, radiation outside the band 0.4 - 0.7 μm (below ultra-violet and above infra-red) has zero luminous energy.

The attenuation of light passing through the atmosphere is attributed to the following phenomena:

(a) Scattering of light by small particles and molecules;

(b) Reflection by larger, liquid and solid particles;

(c) Absorption by solid particles.

Passing through the air along a distance dl, a parallel beam of luminous energy flux F is reduced by a quantity dF, according to the relationship:

$$dF = -F.x.dl \qquad (1)$$

where:

$x = x_a + x_s$ (called the extinction coefficient (depending on wavelength));

x_a = extinction due to absorption;

x_s = extinction due to scattering and reflection.

If there are no light-absorbing solid particles in the air, $x = x_s$ (this is assumed throughout the discussion). It is also assumed that along the path of light l, x is constant.

Equation (1) integrated gives the Bouguer-Lambert law:

$$F = F_o e^{-x.l} \qquad (2)$$

where:

F_o is the value of F at the front end of the path, dl;

$F/F_o = e^{-xl} = T$, is known as the transmission factor. (2')

Differentiating (2), the value of the extinction coefficient x is obtained as a relative change of the luminous flux per unit length:

$$x = -(dF/F) \quad (1/dL) \qquad (2'')$$

Following equation (2), the same type of relationship can be written for the illumination from a point source:

$$E = (I/l^2).e^{-xl} \qquad (3)$$

where:

E = illumination (luminous flux per unit area at a distance l from the point source);

I = luminous intensity.

11.1.3 Threshold of contrast

If a uniform object of brightness, B_o, is seen against a background of the same colour, which has a brightness, B_b, a so-called, brightness contrast, C, could be defined by the relationship:

$$C = (B_o - B_b)/B_b \qquad (4)$$

The brightness contrast, C, may have positive as well as negative values, depending on the magnitudes of B_o and B_b.

A critical brightness contrast, C_c, is defined, with the object hardly distinguishable against the background. Two different values of C_c are used in meteorology: $C_c = 0.02$ and $C_c = 0.05$ (ICAO suggested). Recent studies confirm that the second is probably more useful outdoors.

The critical brightness contrast is affected by factors such as:

(a) Eyesight;

(b) Colour of light;

(c) Angular dimensions of the object;

(d) Glare;

(e) General brightness, etc.

The atmosphere has two effects on the light received from an object (including non-self-luminous objects, visible by reflected light):

(a) Generally, it diminishes the flux of luminous energy, following the Bouguer-Lambert law;

(b) It adds extra light, scattered from the atmosphere between the source (object) and the eye (daylight conditions).

Under a given set of conditions, if we vary the distance of the object from the eye, the first effect does not change the brightness contrast, C, since the apparent brightness of the object and background are reduced in the same ratio by a factor of e^{-xl}. The second effect, however, adds equal amounts of light to the background and object, reducing as a result the brightness contrast, C.

If object and background recede, at a specific distance $l = V$, the object will become hardly distinguishable against the background, i.e. the critical brightness contrast will be reached. The distance V is known as the visual range (VR).

A number of factors affect the visual range, such as:

(a) The observer's eyesight;

(b) The value of the extinction coefficient;

(c) The values of brightnesses;

(d) The reflective properties of the atmosphere (background);

(e) The reflective properties of the object;

(f) The elevation of the Sun;

(g) The angular separation Sun/object;

(h) The size of the object;

(i) The colour of the light, etc.

Homogeneous observations of the visual range can be obtained if the conditions or the observations are properly specified, so as to eliminate the effect of the factors listed above, with the exception of factor (b), the extinction coefficient. The difference between visual range and meteorological visibility is introduced by the definitions:

- Visual range = distance at which the object is just visible;
- Meteorological visibility = distance at which the object is visible and can be recognized.

11.1.4 Koschmieder's law

Based on the assumption of a uniformly illuminated atmosphere (no clouds) and a uniform extinction coefficient, x, Koschmieder has suggested the following relationship between B_o, B_b and $e^{-x.1}$:

$$B_o = (1 - e^{-x.1})B_b \tag{5}$$

Combining equations (4) and (5) results in:

$$C = (B_o - B_b)/B_b = e^{-x.1} \tag{6}$$

With an increase of 1, the distance object/observer, the brightness contrast C, approaches its threshold value C_c, until the visual range V is reached, for which case the following equation holds:

$$C_c = e^{-x.V} \tag{7}$$

Equation (7) can be solved to obtain the visual range, thus:

$$V = -(\ln C_c)/x, \text{ or } V = (1/x) . \ln(1/C_c) \tag{8}$$

With a fixed value of C_c, the visual range then could be found by instrument measurement of the extinction coefficient, x.

The variations in the estimated V, depending on the value of C, have been studied by Middleton, using the expression:

$$dV/V = \frac{-1}{\ln(1/C_c)} \cdot \frac{dC_o}{C_c} \tag{9}$$

The frequency distribution of C found by Middleton is shown in Figure 138. The result is based on observations performed by 1 000 trained observers.

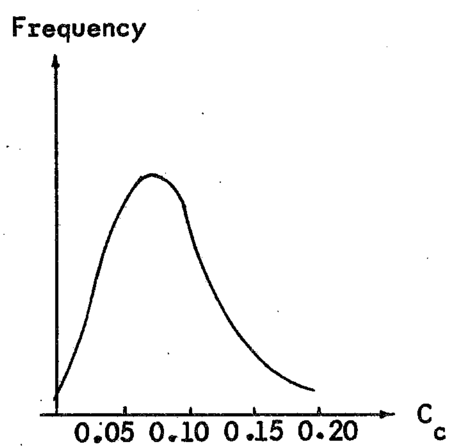


Figure 138 – Frequency distribution of brightness contrast, C

It should be remembered that the critical contrast, C_c, depends strongly on the background luminance (brightness). The luminance of the horizon sky varies over a wide interval, depending on the meteorological conditions and on whether it is day or night:

Clear day: $L_{hs} \cong 10^4$ cd m^{-2}

Moonless, overcast night: $L_{hs} \cong 10$ cd m^{-2}

In a daytime visibility estimation the observer's eye is in a photoic state, in which foveal vision is used, typically with a sharp colour perception and high resolution.

11.1.5 Visibility at night

Daytime visibility is reduced by the air-light, which affects the brightness contrast. At night there is virtually no air-light, so that the visual range of lights is reduced only by the attenuation and is usually much greater than the daylight VR under the same conditions.

As far as the human observer is concerned, the night-time visual range estimation is attained by the para-foveal vision, using the peripheral parts of the retina, which do not have colour sensitivity and sharp resolution, but are much more sensitive to lower intensities of light. The para-fovea takes about 30 minutes to become adapted to the dark, while the fovea needs only two minutes.

As already mentioned, the meteorological visibility at night can be defined as the greatest distance at which lights of moderate intensity can be seen and identified.

Re-writing equation (3) for the case of a point light source at the distance of the night-time visual range D (when it is just visible), the following expression is obtained:

$$E_t = (I.e^{-xD})/D^2 \tag{10}$$

where:

E_t = the threshold illumination.

Taking the logarithm of both sides of the equation results in

$$\ln E_t = \ln\left(\frac{I}{D^2}\right) - xD \tag{11}$$

Substituting in equation (11) the expression for the extinction coefficient, x, from (8) gives

$$x = (1/V)\ \ln(1/C_c)$$

$$\ln E_t = \ln\left(\frac{I}{D^2}\right) - \frac{D}{V}\ .\ \ln(1/C_c) \tag{12}$$

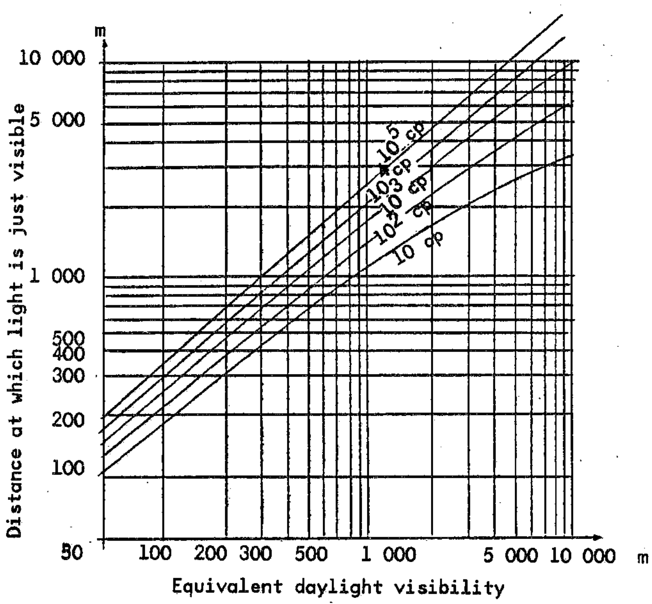
and finally:

$$V = \frac{D.\ln(1/C_c)}{\ln(I/D^2E_t)} \tag{13}$$

The expression (13) gives the visibility at night, using a point source of light. If the light source is a runway light, delineating the runway at a distance, D, then this distance would represent the visual range along the runway (runway visual range - RVR), provided the light is observed from a point about five metres above the runway surface.

The illumination threshold, E_t, varies from one observer to another and is generally different at different times of the day, depending on the background luminance:

Time	Illumination threshold, E_t		Background luminance
	(lx)	($km\ cd^{-1}$)	($cd\ m^{-2}$)
Night	8.10^{-7}	3	1-50
Twilight	8.10^{-5}	41.6	51-999
Normal day	8.10^{-4}	416	1 000-12 000
Bright day (sunlit fog)	8.10^{-3}	4 160	< 12 000



139 - Night visibility/equivalent day-time visibility graph (cp = candle power)

An estimate of the conversion of night visibility observations, when the observed light is "just visible", into the daylight equivalent visibility, can be obtained from Figure 139. It must be kept in mind, however, that an allowance should be made for the varying conditions through the use of an "apparent" candle power according to the following rules:

(a) Find out the true candle power of the light observed;

(b) Introduce corrections for the background brightness as follows:

In darkness or moonlight	In weak twilight	In strong twilight	In full summer daylight
No correction	Divide candle power by 10	Divide candle power by 100	Divide candle power by 1 000

(c) The observer's vision should be fully adapted to the conditions (i.e. more than two minutes spent in darkness);

(d) Correct for the colour of light as follows:

Red light	Orange (yellow) light	White light	Green light	Blue light
No correction	Multiply candle power by 5	Multiply candle power by 20	Multiply candle power by 50	Multiply candle power by 250

(e) Using the diagram in Figure 139, find the horizontal line corresponding to the distance of the selected light (just visible) and follow it until intersection with the graph corresponding to the corrected candle power of the light. From the point of intersection, follow the vertical line until reaching the abscissa; read out the equivalent daylight visibility.

In order to make practical use of the routine outlined above for the estimation of visibility in night-time conditions it would be necessary to have a row of lights in the direction of observation, spaced at known distances.

The visual estimation of visibility is prone to an appreciable error.

11.2 Principles of visibility-measuring instruments

Instruments for the measurement of visibility fall into two main categories:

(a) Those measuring attenuation or extinction coefficient of the atmosphere;

(b) Those measuring the scattering of light from the particles suspended in the atmospheric air.

Both categories of instruments measure visibility over a limited path being, in that respect, inferior to well-executed manual methods (i.e. "visual" methods).

11.2.1 Lohle's relative telephotometer

This is a comparative telephotometer, capable of measuring the contrast of brightness of a distant object against the horizon sky. The instrument is suitable only for day-time visibility estimation with the help of well-known observation objects located at known distances. The principle of operation of the instrument is illustrated in Figure 140.

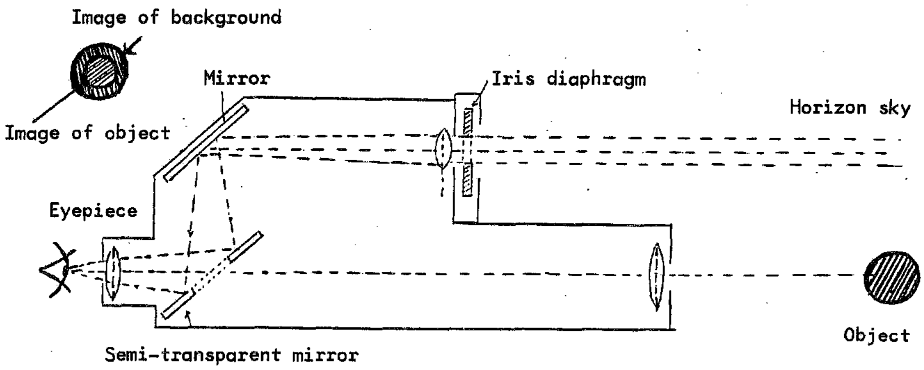


Figure 140 - Lohle telephotometer

Through the use of two optical systems, the images of object and background (horizon sky) are brought together in the field of view of the observer. The brightness of the background can be varied by an iris diaphragm to obtain a match between object and background. The control handle of the iris diaphragm indicates the value of the brightness contrast, C, against an attached scale. With the distance, l, between observer and object known, the extinction coefficient, x, could be obtained from the relationship:

$$C = (B_o - B_b)/B_b = e^{-x.l}$$

With a known extinction coefficient and substituting its value, as well as the value for the critical brightness contrast $C_c = 0.05$ in the equation for the calculation of the visibility:

$$V = (1/x)\ln(1/C_c),$$

the value of the meteorological visibility is obtained.

A number of telephotometers have been designed for a day-time measurement of the extinction coefficient. They are not in routine use, however, at observing stations, where direct visual observations of visibility are favoured for their simplicity and comparable accuracy.

11.2.2 The Collier-Taylor transmissometer (See Figure 141.)

This is an instrument based on a relative photometric principle comparing the illuminations obtained from two light sources (lamps) of known intensities, I_1, and I_2. The distant light source of intensity, I_1, located at a distance L_1 from the instrument is compared to the light source I_2, contained in the instrument's housing at a distance, L_2, from the reference point of measurement of distances. The intensity of this light source can be varied with the aid of an optical wedge (both I_1 and I_2 are assumed constant with time).

The respective illuminations obtained from the two sources at the eye of the observer thus are:

$$E_1 = (I_1/L_1^2).e^{-x.L_1} \quad (1)$$

$$E_2 = I_2/L_2^2 \quad (2)$$

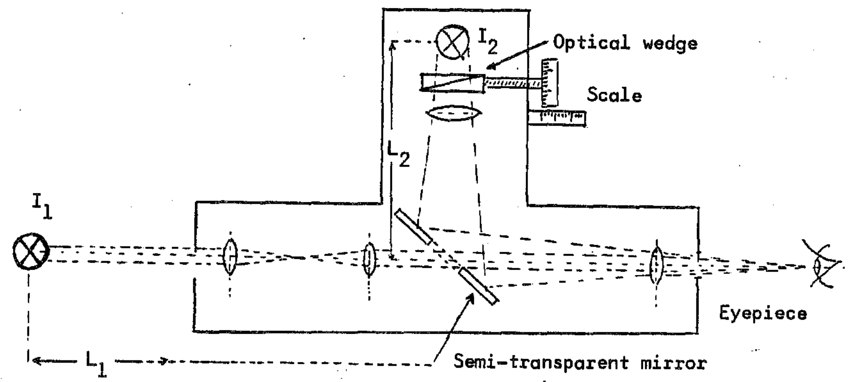


Figure 141 - Collier-Taylor transmissometer

If the intensity E_2 is varied by means of the optical wedge until the two illuminations become equal:

$$E_1 = E_2 \tag{3}$$

and the value of I_2, as read from the scale of the instrument is substituted in equation (2), while equations (1) and (2) are combined according to equation (3), the extinction coefficient is obtained as follows:

$$x = \frac{1}{L_1} \ln \left(\frac{I_1 . L_2^2}{I_2 . L_1^2}\right) \tag{4}$$

With a known baseline, L_1, the visibility can be calculated through the substitution of the values of the extinction coefficient and C_c in the basic visibility equation.

Use of a modulated light beam would also enable day-time measurements of visibility.

11.2.3 The scopograph transmissometer

The scopograph is designed for aeronautical use and can indicate and record visual ranges from 50 m to 9 km.

The instrument consists of one transmitter, one or two receivers located at the far end of baselines of 75 m and 450 m respectively, one indicator and one or two recorders, which can be installed up to 10 km away from the measuring site. The installation site is usually parallel to the runway. The general layout of the instrument's units is shown in Figure 142.

The transmitter, provided with a high-power pulse-light source working at a voltage of 3 kV and mounted at the focus of a parabolic mirror, transmits high-intensity light pulses of 10^{-7} s duration and a repetition frequency of 1.5 Hz. The spectral range of the emitted light is 350 to 600 μm. The transmitter is enclosed in a weatherproof aluminium housing and is provided with a reinforced high-transparency glass lid placed in front of the mirror. The unit is thermostated and the glass is provided with a separate defrosting heater.

The receiver, through its photocell, picks up the light pulses, amplifies them with the help of a solid-state amplifier and measures their amplitude which is then compared with the averaged pulse intensity of the transmitter, the attenuation of the former being a measure of the transmissivity of the atmosphere along the baseline of the instrument. The result is displayed and recorded by the indicator and recorder.

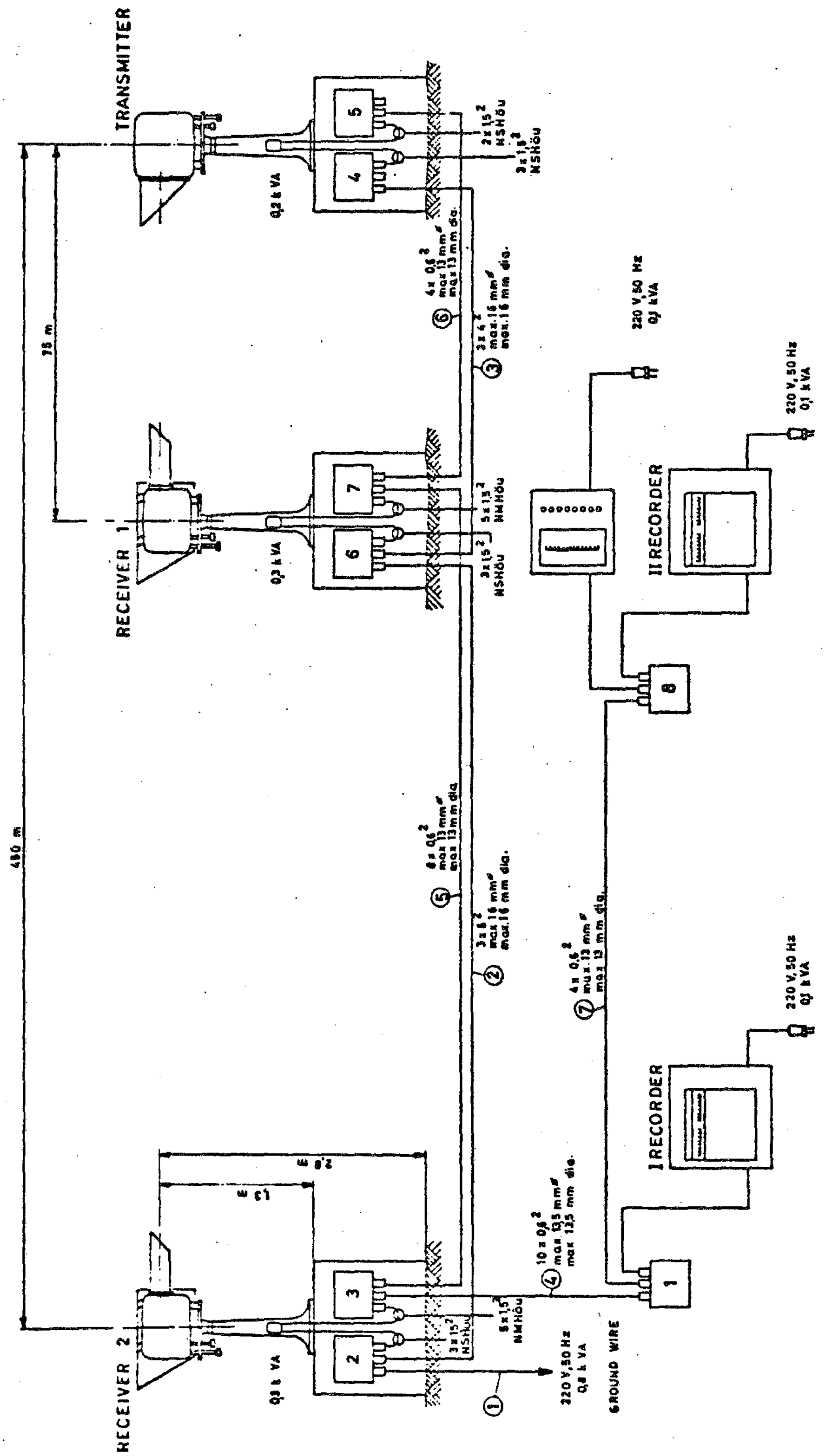


Figure 142 - Scopograph transmissometer

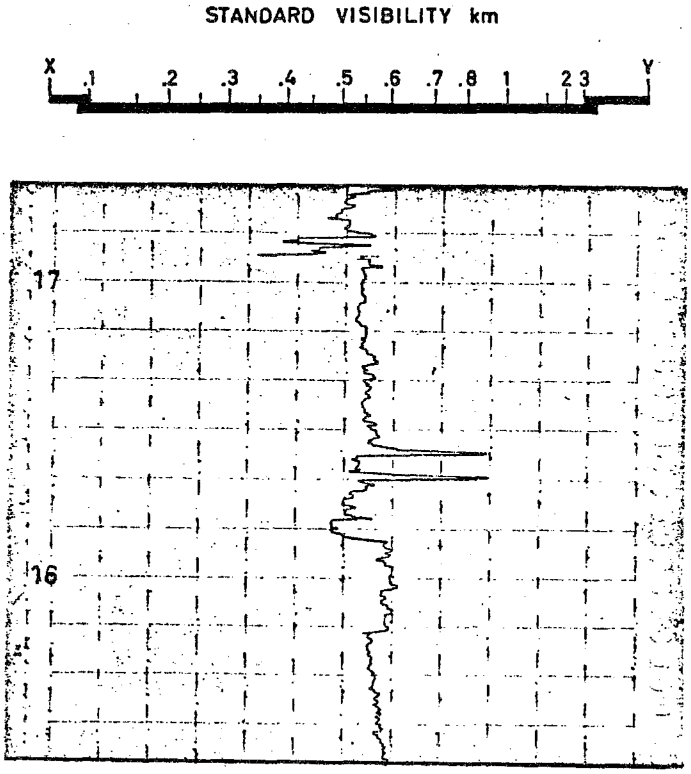


Figure 143 - Scopograph visual range recording: paper transport 60 mm h^{-1}; strip-chart length 24 m; recording time-span 16 days.

The receiver sensor is screened from the background light by a honeycomb and an optical filter; the unit is enclosed in an aluminium housing, the optical system being provided with a defrosting heater.

The theory of the instrument is as follows:

If the amplitude of the light pulse at the transmitter is A_o and the amplitude of the received light pulse is A_r, the following relationship holds:

$$A_r = A_o e^{-xR} \quad (1)$$

where:

R = the distance transmitter-receiver along the baseline;

x = extinction coefficient of the atmosphere along the baseline.

Following Koschmieder:

$$C_c = e^{-x.V} \quad (2)$$

C_c = 0.02, the assumed critical brightness contrast;

V = visual range.

Equation (2) could be presented in the form:

$$\ln(C_c) = -xV \tag{3}$$

and substituting the numerical value for C_c:

$$3.912 = x.V \qquad (\ln 0.02 = -3.912) \tag{4}$$

Re-arranging (4):

$$x = \frac{3.912}{V} \tag{5}$$

and substituting equation (5) into equation (1) and re-arranging:

$$\ln(A_o/A_r) = 3.912\ R/V \tag{6}$$

Taking into account that $A_o/A_r = T$, the atmospheric transmissivity, the following expression for the visual range V is obtained:

$$V = \frac{3.912\ R}{\ln(1/T)} \tag{7}$$

(or $V = \frac{3.0\ R}{\ln(1/T)}$ if $C_c = 0.05$).

The atmospheric transmissivity is measured through the amplification of the received signal.

11.2.4 The Brewer-Beutel scatter-meter

In the absence of solid particles, the extinction coefficient depends mainly on scattering and reflection by hydrometeors and can thus be measured by estimating the light-scattering angle, involving the refractive index and size of the scatterers.

One visibility-measuring instrument based on the light-scattering principle is the Brewer-Beutel scatter-meter (Figure 144).

The light from an opal window, C, is scattered in a wide angle, along a 40 cm path. The scattered light is sent into the optical system of the instrument through a concave mirror, K, and is passsd through a screening device, letting only half of the beam reach the eyepiece. Light for the other half of the field of view is provided by another opal window, B, illuminated by the same light source. The direct-beam intensity is controlled by an optical wedge, its scale being graduated directly in visibility values. The scale is read after the two beams - scattered and direct - are matched in intensity at the spot of comparison, the plate, G, through the optical wedge.

Instruments of this type, properly shielded from direct background light, can be used by day and by night. One main shortcoming is that only a small air sample is involved in the measurement, while the conclusions are extended for a large area. Another is that the results depend on the phenomena observed.

An airport instrument of this type is the videograph. Transmitter and receiver share a common housing and optical systems are one above the other, facing the same direction. The light from the transmitter is back-scattered by the hydrometeors and is picked-up and measured by the receiver.

The visibility values are recorded on a metallized strip-chart.

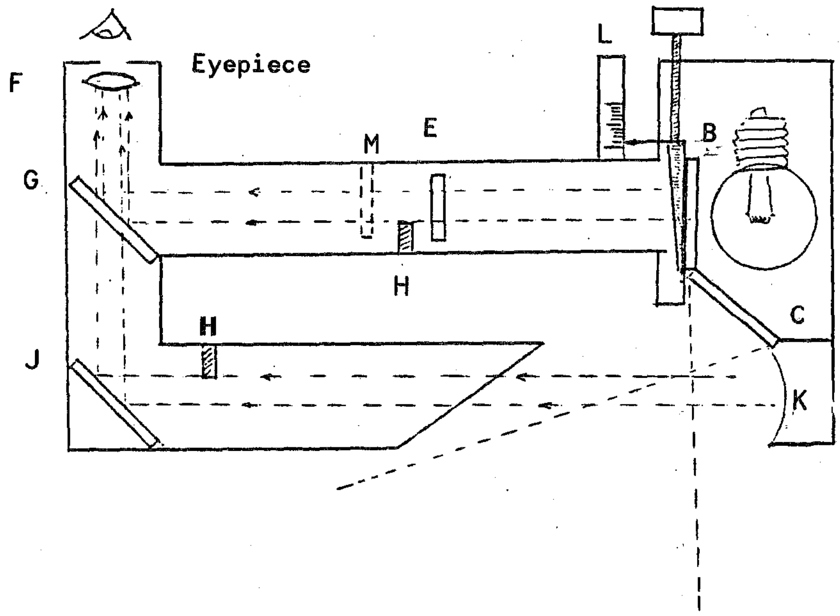


Figure 144 - Brewer-Beutel scatter-meter: B, C - opal glass plates; M - glass filter - step-change; H - screen; F - lens; G - glass plate; J - mirror; K - concave mirror; L - control screw of the optical wedge

11.3 Sources of error in visibility measurements

Visual measurements of visibility give rise to a dispersion of the measurement values owing mainly to the following factors:

(a) Interpolation between visibility objects;

(b) The observer's bias arising from previous experience;

(c) Condition of the observer's vision.

Errors of at least 10 per cent are probable in conditions of good visibility and increase sharply with poor visibility.

Measurements with transmissometers may be affected by a decrease in the transparency of the instrument's optics because of atmospheric pollution or a change of intensity of the light source.

Instruments based on the back-scatter principle give erroneous results in conditions of diminished visibility such as sandstorms and snowstorms.

Instrumental estimation of visibility is affected by errors exceeding 30 per cent. Also, measurements made in conditions of rapidly fluctuating visibility (e.g. banks of drifting fog) will not necessarily be representative of the general level of visibility over a wide area.

11.4 Routine care of visibility-measuring instruments

Visibility-measuring instruments are sensitive to optical misalignment and changes of intensity of the light beam. Routine checks of the condition of the optics (careful cleaning, defrosting), alignment of the optical systems of receiver and transmitter, as well as periodic checks of the projector lamp, pulse-repetition frequency and parameters of the receiver, are essential.

Systematic checks of the recording device are also necessary.

Instruments provided with accessories permitting calibration should be calibrated after any major intervention from maintenance crews.

CHAPTER 12

UPPER-WIND MEASUREMENTS

12.1 General - units of measurements

Upper-wind measurements are important to synoptic and aeronautical meteorology, as well as to scientific research. While it is possible to estimate the direction and speed of the wind at a certain level by observing the motion of the clouds, the upper-wind profile in the vicinity of the observing site may be measured by tracking a free-flying balloon inflated with hydrogen or helium. This may be achieved by one of the following three methods:

(a) With the help of a theodolite (optical tracking);

(b) Through direction finding, using a balloon-borne transmitter and a ground-based radio receiver with a highly directive antenna (radio-theodolite tracking);

(c) Through the radar echo obtained from a balloon-borne radar reflector (radar wind measurements).

The speed of the upper winds is reported in either knots or metres per second. The direction is reported in degrees from north or on the scale 0 - 36 where 36 is the wind from the north and 09 from the east.

The unit of geopotential used in upper-air observations is the geopotential metre (gpm). As the geopotential metre is defined as 0.980665 of the dynamic metre, the value of the geopotential is, for practical purposes, numerically equal to the height expressed in metres.

With observations extending much beyond a horizontal range of 10 km, the height must be corrected for the curvature of the Earth (at 10 km, corrections amount to about 8 m increasing with the square of the horizontal range).

12.2 Meteorological balloons

Meteorological balloons are made of natural or synthetic rubber. The most suitable synthetic rubber available at present is neoprene. Both types of balloon are made of rubber in the form of latex emulsion, which should be suitably compounded with the necessary ingredients, such as vulcanizing agents, accelerators and anti-oxidants. Special-purpose (constant-level) balloons are made of unstretchable plastic materials.

The main requirement for ordinary meteorological balloons is uniform elasticity. Linear stretching of the envelope by up to 700 per cent of the diameter, while retaining good gas tightness, marks a good-quality balloon.

When inflated, the balloon should preferably have a perfect spherical shape. Marked departure of the balloon from a spherical form increases the tendency for the balloon to somersault and have an irregular ascent velocity. It is essential for the balloon envelope to be light-weight and resistant to low temperatures, ozone and ultra-violet radiation. Synthetic rubber is superior in this respect to natural rubber.

Small meteorological balloons are manufactured by dipping a spherical mould made of glass into a latex emulsion. Immersion is repeated several times until the desired uniform thickness is attained.

Large balloons are made by spraying latex emulsion into hollow rotating moulds, which can split open along their equator. The centrifugal forces, created by the rotation help in the even distribution of the rubber inside the mould. After drying, the balloon is taken out of the mould by separating the two halves of the mould.

The thickness of the balloon wall, T, can be calculated from the formula:

$$T = \frac{G}{\pi . D^2 . g} \text{ (cm)}$$

where:

G = the weight of the balloon without the neck (g);

D = balloon diameter (cm);

g = rubber density = 0.935 (g cm^{-2}).

The bursting thickness of a good balloon is about 10 μm.

Natural rubber preserves its elastic properties even at low temperatures, but is readily affected by ultra-violet radiation and ozone. Neoprene is ultra-violet- and ozone-resistant but its elasticity is decreased at low temperatures. Natural rubber is recommended for use in night-time ascents.

In order that the good properties of balloons be preserved as long as possible, balloons should preferably be stored in a dark place with a temperature between 10° - 20°C and a relative humidity of about 60 per cent. Shelf-life of balloons stored in this way may be expected to be about one year (without perceptible change of the balloon's properties).

To restore the elastic properties of latex balloons stored continuously for longer periods of time, a pre-ascent conditioning - a warm-up of 60° - 80°C - is recommended.

With the elastic properties of the balloons strongly affected by storage, a kerosene bath pre-ascent conditioning for one to two minutes on the outside of the balloon with a consequent drying at 20°C may help in the restoration of its qualities.

The operator should handle balloons with soft cotton gloves. For inflation, the balloon is laid on top of a polyethylene covered table. Care should be taken not to inflict any scratches on the balloon while handling it.

Good-quality balloons should be free from foreign matter, pin-holes or other defects and be of homogeneous thickness. They should be provided with necks of a greater thickness, capable of supporting (depending on the size of the balloon) a load of up to 18 kg without damage to the rubber. The neck's diameter ranges (depending on the balloon's size) from 1 - 5 cm and 10 - 15 cm length. The thickness of the balloon should increase gradually toward the neck.

The various sizes of meteorological balloons are given in the table below:

Balloon use	Weight	Diameter of unstretched rubber (cm)	Diameter of unstretched neoprene (cm)
Height of cloud base	10	13	19
Pilot balloon	30	20	28
Pilot baloon, high ascension rate	100	45	55
Sounding balloon, up to 15 km	350	115	-
Sounding balloon, up to 20 km	500	130	160
Sounding balloon, up to 25 km	800	160	180
Sounding balloon, up to 30 km	2 000	250	-

12.3 Gases for inflation of meteorological balloons

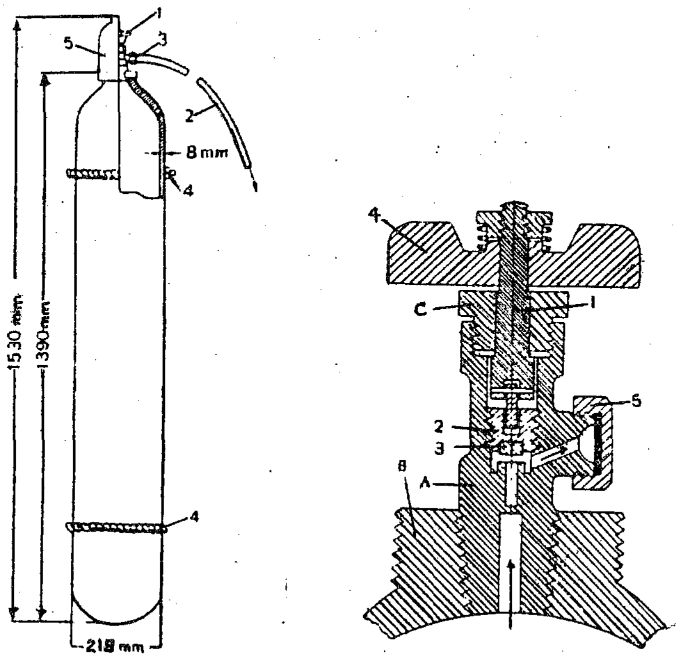
Helium is the ideal gas for balloon inflation since it does not react with any substance. It does not burn, nor does it destroy the rubber and it is non-toxic. Its specific weight is 0.1785 kg m^{-3} and the total lift at a pressure of 1 013 hPa and temperature of 0°C is 1 115 g m^{-3}. Helium is in short supply, however, as a natural gas (relatively more abundant in the U.S.A.), and its wider use is therefore restricted.

Hydrogen is another gas suitable for balloon inflation, being the lightest with a specific weight of 0.0899 kg m^{-3} and a total lift of 1 203 g m^{-3}. Hydrogen has a strong affinity for oxygen with which it combines to form an explosive mixture.

Compressed-balloon inflation gas in steel cylinders is the most convenient way of providing gas at meteorological stations (Figure 145). The hydrogen steel cylinder is seamless, with a capacity of about 40 litres. The external dimensions are: height 1 530 mm; diameter 218 mm; thickness of the wall 8 - 10 mm; and empty weight 80 kg. Each cylinder is capable of containing about six cubic metres of hydrogen at a pressure of 120 atmospheres (100 atmospheres in the tropics). Hydrogen is let out from the cylinder through a discharge valve operated by the meteorological observer (Figure 145 - right-hand side). For aerological purposes, an additional pressure-reducing valve is used, having one low (4 atm.) and one high (150 atm.) pressure gauge. A spring-loaded pressure-controlling valve maintains the desired low pressure.

Hydrogen cylinders are painted a special colour (depending on the local regulations). The thread of the cylinder outlet is left-handed to prevent accidental connexion of the cylinder to other than hydrogen installations. Rubber protective rings (4) prevent direct contact between cylinders while in transport. A steel protective cap (1) is screwed onto the top of the cylinder to prevent damage to the brass discharge valve. Great caution must be exercised when handling the cylinders: compressed gas may explode on mechanical impact or if there is a rise in temperature owing to prolonged exposure to solar radiation.

Chemically pure hydrogen burns with a colourless flame, developing a temperature of about 1 500°C. One kilogram of hydrogen and eight kilograms of oxygen are capable of releasing by burning 121.42 10^6 J with nine kilograms of water vapour as a product of the combustion. (For comparison, one kilogram of gasoline releases 50.24 10^6 J by combustion.) The hydrogen/oxygen mixture may become self-ignited (ignition temperature 585°C) with a strong explosion. The resulting hot-gas wave



Hydrogen cylinder

(a)

Hydrogen-cylinder discharge valve

(b)

Figure 145 - (a) Hydrogen cylinder: 1 - valve; 2 - durite hose; 3 - union; 4 - safety ring; 5 - protective cap; (b) Hydrogen-cylinder discharge valve: A - main part; B - cylinder neck; C - secondary part of valve; 1 - rod; 2 - threaded plug; 3 - washer; 4 - valve disk; 5 - cap

moves away from the explosion point very fast, capable (apart from its shock-wave effect) of inflicting severe burns (with possibly fatal effects on the breathing tract) on the hydrogen-handling personnel.

Because of its very low ignition energy, hydrogen can be ignited by very weak static electricity sparks. Static electricity is built up by the inflation of talcum-powdered balloons due to the friction between the talcum particles. In order to prevent ignition of hydrogen by static electricity, low-inflation gas velocities are used (through a reduction valve) and thorough earthing of the inflation pipe.

12.4 Hydrogen generators for aerological purposes

The use of compressed hydrogen in steel cylinders for inflating meteorological balloons is convenient, but may pose transportation problems with remote field stations. In such cases, the generation of hydrogen on the spot may be preferred.

There are two main types of transportable hydrogen generators: the high-pressure and the low-pressure types. The former has the advantage of being able to store the gas under pressure for use whenever necessary, whereas the latter type produces hydrogen for immediate use.

Of the various methods by which hydrogen can be generated, the following three have a wider practical application for meteorological purposes:

(a) Ferrosilicon and caustic soda method;

(b) Aluminium and caustic soda;

(c) Electrolysis of water.

12.4.1 The ferrosilicon and caustic-soda high-pressure hydrogen generator (Figure 146)

This generator uses a steel, bottle-shaped, trunnion (7) cylinder like those used for compressed hydrogen held in a cradle (6) or a two-wheel trolley. The cylinder's neck is threaded and a special plug-and-collar device (2), carrying the discharge valve (3) manometer (4) and outlet (12), is screwed on it. The plug-and-collar device known as the head of the cylinder carries the safety valve (5), which bursts open when the pressure inside the bottle reaches values related to the safe testing pressure of the bottles (300 atmospheres). Accessories not shown in the figure comprise a metal pail for pouring water into the bottle, a funnel, fitting the bottle's neck, used to facilitate the insertion of chemical reagents into the bottle, a cylindrical metal basket on a chain used to lower the crushed ferrosilicon into the bottle.

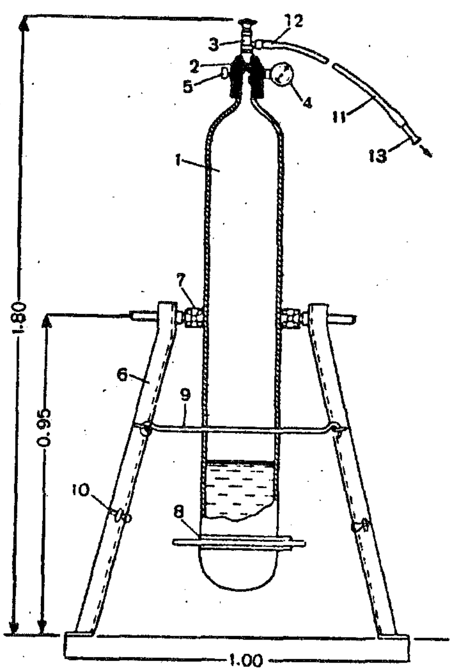


Figure 146 - High-pressure, cylinder-type hydrogen generator

The charge of the generator consists of the following components:

(a) Alkaline charge (granulated NaOH) in sealed cans (1.8 kg);

(b) Priming charge of powdered ferrosilicon contained in a small metal tin (0.300 kg);

(c) A charge of crushed ferrosilicon, sufficient to fill the basket (2.5 kg);

(d) A charge of water (13 litres).

The caustic soda charge with the powdered ferrosilicon admixed is poured into the generator. The crushed ferrosilicon charge is placed into the metal basket and lowered into the bottle. The water charge is poured on top of all and the head is screwed in place. The steel bottle is then set in a vertical position and is shaken for two or three seconds. The reaction starts slowly, an indication being the warming of the bottom of the bottle. In order to remove all traces of air from the bottle, the discharge valve is left open for about two minutes, then closed again. As the temperature of the generator rises (it may exceed 400°C) the pressure starts to build up and soon reaches 100 to 120 atmospheres. At this stage, the generator is shaken once again in order to bring down into the caustic soda solution all the ferrosilicon which might have remained stuck in the basket.

The hydrogen may be drawn immediately at the end of the reaction (pressure about 140 to 150 atm.), but it is better to let the generator cool off in order to prevent water vapour and droplets from entering the balloon. About three cubic metres of hydrogen is obtained from one charge.

The generation of hydrogen by the method described is based on the following reaction:

$$Si + NaOH + H_2O = Na_2SiO_3 + 2H_2$$

The considerable amount of iron contained in the ferrosilicon does not take part in the reaction, which in fact is more complicated than described by the above equation. The reaction is accelerated if the water is preheated. This is recommended especially in cold climates. The following table may be used for the water temperature:

T_{air}	-30°	-20°	-10°	0°	10°	20°
T_{water}	90°	80°	70°	60°	50°	40°

At very low temperatures it is recommended to add to the ferrosilicon five to ten per cent aluminium powder. The aluminium increases the temperature of the reaction and prevents the rapid solidification of the residue in the generator.

The hydrogen generator must be handled with great care and its operators should wear special attire, gloves and goggles.

As soon as the hydrogen is used, the generator should be cleaned thoroughly and the caustic residue disposed of in a specially-prepared pit. It should be remembered that the residue tends to solidify and that it is base-active.

All threads must be lubricated using viscous mineral grease.

12.4.2 The caustic-soda and aluminium hydrogen generator

The use of granulated aluminium and soda (NaOH) gives hydrogen according to the following reaction:

$$2Al + 2NaOH + 2H_2O = 2NaAlO_2 + 3H_2$$

The reaction is accompanied by a rise in temperature of the generator and a build-up of pressure up to 140 atm.

A gas generator similar to the one already described is used. The composition of the charge for 1.1 m^3 of hydrogen is 1 000 g of aluminium, 100 g of sodium hydroxide and 2 litres of water.

The handling of this generator is the same as for the previous one.

It is possible to use the same composition for low-pressure production of hydrogen, in which case a gas-holder would be necessary for the gas.

The same precautionary measures are taken with this gas generator as with any using caustic soda.

Neutralizing substances (like vinegar) must always be kept handy while charging or cleaning the generator.

12.4.3 The Stuart hydrogen electrolytic generator

With electrical energy readily available the Stuart-cell based electrolytic generator offers a convenient and safe method for producing hydrogen of high purity (almost 99.9 per cent).

Generally speaking, the electrolytic cell is a low-pressure generator delivering hydrogen (as well as oxygen) at a pressure of 160 mm water column. The block diagram of the generator is shown in Figure 147. The generator consists of a d.c. power source (rectifier), battery of electrolytic hydrogen cells, water seal, low-pressure gas-holder, compressor and high-pressure gas-cylinder. An alternative set-up for low-pressure use is the one without compressor and high-pressure cylinder.

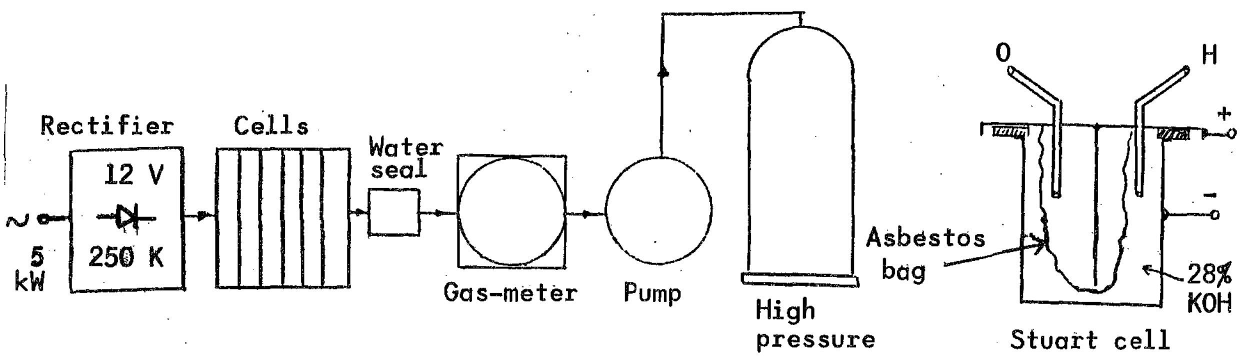


Figure 147 - Block diagram of electrolytic hydrogen generator

Depending on the electrical power available, generators having different hydrogen output ratings can be used, one with a power consumption of about 5 kW being capable of delivering to the gas-holder about 0.6 m^3 of hydrogen per hour. The water consumption of this model is about 12.5 dm^3 d^{-1} plus 2.6 dm^3 of demineralizer.

The principle of operation of the generator is the well-known principle of electrolysis of the water with an end result of two units in volume of hydrogen and one unit of oxygen (released to the atmosphere).

The electrolytic hydrogen generator is a reliable device, but one needing competent maintenance and checking to ensure its safety.

12.5 Theory of upper-wind measurement

Upper-wind speed and direction are measured by tracking a meteorological balloon in free flight in the atmosphere. It is assumed that a short time after the release of the balloon a steady state is reached, in which the balloon is ascending vertically owing to its buoyancy and drifting horizontally with the moving air. We are interested in the horizontal component of the upper wind at different height levels, for which an accurate record of the balloon's position at the respective height levels is necessary. Two successive positions of the balloon at levels (1) and (2) are shown in Figure 148(a), the balloon trajectory being given in a co-ordinate system.

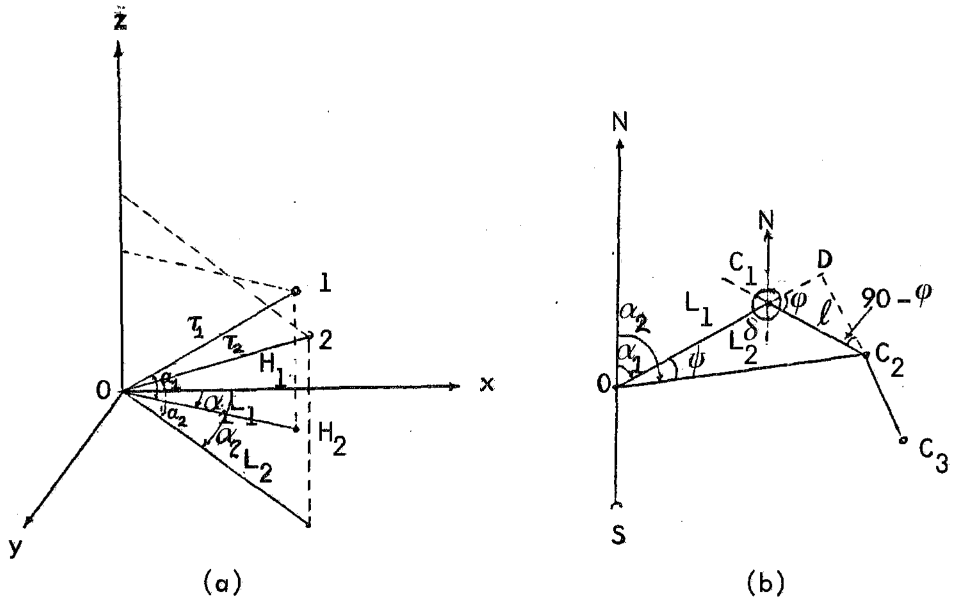


Figure 148 - Balloon trajectory in a co-ordinate system

It is assumed that the heights of the balloon in positions (1) and (2) are known, having been found by one of three possible methods:

(a) Theodolite observation with an assumed constant ascent velocity of the balloon: $H = w.t$ (w = ascent velocity; t = time);

(b) Radiotheodolite observation; the height H having been obtained through pressure measurements;

(c) Radar observations; the height H obtained through the measurement of the slant range: $H = r.\sin a$ (r = slant range, a = elevation angle).

The angular co-ordinates, azimuth and elevation, are measured by all three methods and these enable the projections of the balloon's positions on a horizontal plane to be found (Figure 148(b)).

$$L = H \cot a \tag{1}$$

Suppose that the broken line $OC_1C_2C_3$.. is the horizontal projection of the trajectory of the balloon, then the segments OC_1, C_1C_2, etc. would represent the averaged wind speed and the direction of the wind for the time intervals between the corresponding balloon tracking positions C, C_1, C_2, etc., thus they would also represent the wind parameters of the atmospheric layers between the tracking points.

A slide-rule calculation of the wind parameters is possible, based on the trigonometric relationships deduced from the graph in Figure 148(b). The value of the first segment $L_1 = H_1.\cot a_1$, the averaged wind velocity in the layer $0,C_1$ being $\frac{L_1}{t_{oc}}$ and the direction obtained from the relationship $d = a_1 + 180°$.

The segment $C_1C_2 = l$ is found from the triangles $0,C_1,C_2$ and $0,D,C_2$:

$$\frac{l}{\sin(\alpha_2 - \alpha_1)} = \frac{L_1}{\sin(\varphi - \psi)} \tag{2}$$

where:

$\psi = \alpha_2 - \alpha_1$, the difference in azimuth angles of L_1 and L_2.

Hence:

$$l \frac{L_1 . \sin\psi}{\sin(\varphi - \psi).} \tag{3}$$

The angle φ can be obtained from the triangle $0,D,C_2$ based on the following reasoning:

$$\cot\varphi = DC_1/DC_2 = (L_2 \cos\psi - L_1)/L_2 \sin\psi = \cot\psi - L_1/L_2 \sin\psi \tag{4}$$

Finally:

$$\varphi = \operatorname{arc\,cot}\left(\cot\psi - \frac{L_1}{L_2 \sin\psi}\right) \tag{5}$$

In this way, through the horizontal balloon trajectory projections, L_i, and the corresponding azimuth angles, α_i, the values of the segments l_i can be obtained which, divided by the corresponding time intervals, t_i, between the tracking points, C_i, give the averaged wind speeds of the layers between the tracking points.

The wind direction angles, d_i, can be obtained from the relation:

$$d_i = \alpha_i + \varphi_i + 180° \tag{6}$$

The slide-rule calculation of the wind parameters is a rather cumbersome procedure. Generally, graphical methods are preferable for this purpose.

12.5.1 Graphical method for the evaluation of the pilot-balloon observation ("pibal")

One method for the graphical evaluation of the pilot-balloon observation is based on the use of the A-30 graphical evaluator (Figure 149). The A-30 plotting board consists of three parts:

(a) Metallic circular board bearing the nomograph;

(b) Centre-pivoted celluloid disk, bearing the azimuth-angle scale;

(c) Celluloid ruler pivoted at the centre of the disk.

The centre of the disk is the assumed observation site. The left-hand side of the nomograph is a grid of horizontal and vertical lines determining the value of the scale division used in measuring the wind speed. The side of each square represents a distance of 60 m (a scale of 1:30 000). The rim of the right-hand side semi-circle of the board bears the doubled angular scale of the elevation angle ($0 - 90^\circ$ are expanded into the semi-circle's 180°) and the family of curves based on the equation

$$L = H \cdot \cot a$$

are also printed.

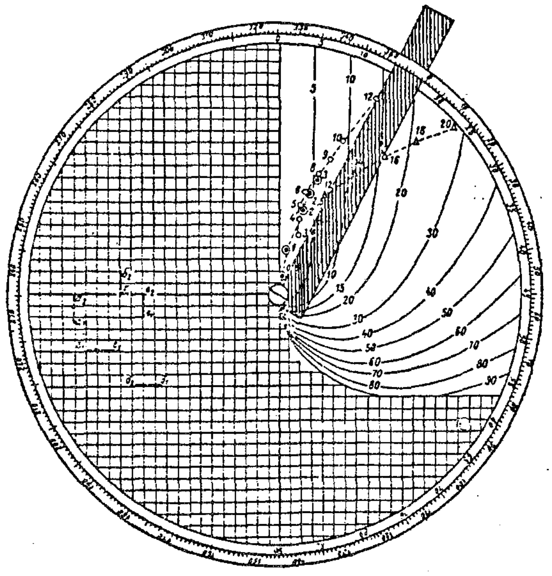


Figure 149 - A-30 Pibal plotting board

Each curve is a locus of the horizontal distance of the balloon from the site of observation for different values of the elevation angle and constant, fixed height of the balloon. Thus, if the ruler is placed in such a way that its edge connects the centre of the disk with the scale division on the board rim corresponding to the given elevation angle, the distance from the centre to the intersection point of the ruler's edge and the curve corresponding to the balloon's height represents the horizontal distance of the balloon from the point of observation. The curves are marked 5, 10, 15, 20, etc., meaning, correspondingly, 500 m, 1 000 m, 1 500 m, 2 000 m, etc.

Successive tracking points are plotted in ink on the celluloid disk in accordance with their height, azimuth and elevation co-ordinates, using the celluloid ruler and marking the points in arabic numerals.

In order to obtain the value of the wind speed at a given height, i.e. the average wind speed of an atmospheric layer, it is necessary to measure the length of the corresponding wind-path segment using the grid of the nomograph dividing by the time interval between the time co-ordinates of the beginning and end of the segment. If the time interval is one minute (the usually-accepted time difference in the observation of the wind parameters of two successive tracking points), the wind speed is equal (in m s^{-1}) to the number of grid squares covered by the wind-path segment.

The direction is found by making the wind-path segment in question parallel to the diameter of the metallic board connecting the 0° and 90° elevation-angle marks, reading the wind direction on the scale of the celluloid disk in direction from the balloon position n + 1 toward position n.

The A-30 upper-wind plotting board can be used in the graphical evaluation of the wind components not only from pilot-balloon observations but from radiotheodolite observations as well.

If the height of the balloon goes beyond the capacity of the plotting board (last height curve is marked 9 000 m), a simple change of the scale 1:10 permits the use of curve 1 000 m as a 10 000 m curve, by a corresponding change in the tracking time interval and the scale of the measuring grid of the nomograph.

12.5.2 Buoyancy of a meteorological balloon

Following Archimedes' law, the total lift of a hydrogen-inflated balloon can be found from the relationship:

$$E = V(g_a - g_h) \tag{1}$$

where:

- E = total lift;
- V = volume of the balloon;
- g_a, g_h = specific gravities of air and hydrogen, respectively.

The free lift of the balloon, A, the one used to lift the payload is obtained from (1) taking into account the weight, B, of the balloon:

$$A = V(g_a - g_h) - B \tag{2}$$

The quantity $e = (g_a - g_h)$ is known as specific lift and is 1.2029 kg m^{-3} for pure hydrogen.

The free lift of the balloon is increased slightly during day-time because of the increase in temperature of the hydrogen by insolation.

12.5.3 Vertical velocity of a meteorological balloon

Soon after release, when equilibrium between lift and drag has been reached, a meteorological balloon rises with an almost constant ascent velocity, w.

The drag, F, can be expressed as a function of the dynamic pressure, q, the drag coefficient, k, and the cross-sectional area of the balloon:

$$F = k.q.S \tag{1}$$

$$q = \rho.w^2/2 \tag{2}$$

$$S = \pi D^2/4 \quad \text{(D = diameter of the balloon)} \tag{3}$$

Combining (1) (2) and (3) gives

$$F = (\pi\ k/8)\,\rho.D^2.w^2 \tag{4}$$

With a steady state reached,

$$F = A. \tag{5}$$

Therefore

$$A = \frac{\pi\ k}{8}\,\rho.\ D^2.w^2 \tag{6}$$

Finally

$$w = \frac{1}{D}\sqrt{\frac{8\ A}{k.\rho}} \tag{7}$$

The balloon circumference is more easily measured than the balloon diameter, so substituting D by its equivalent C/π where C is the circumference of the balloon, equation (7) becomes

$$\frac{\pi}{C} \sqrt{\frac{8\ A}{k.\rho}} \tag{8}$$

The drag coefficient k depends on the Reynold's number. An approximate value for k, as far as small pilot-balloons are concerned, is 0.6.

The letter ρ stands for the air density. The value of the standard air density ρ_o = 1.205 kg m^{-3} may be substituted in either (7) or (8) in order to obtain the value of the ascent velocity under standard conditions.

The estimation of the balloon-ascent velocity at the observing site is made most often using the ascent velocity table given below:

Free lift in grams for various total weights and ascent rates

Rate of ascent (m s^{-1})	2	3	4	5	6
Total weight of balloon and load (g)					
10	25	80			
30	35	125			
100		150	300	500	
1 000		250	400	650	1 000
2 000			550	900	1 400
4 000			900	1 400	2 200
6 000			1 100	1 800	2 800

The table values for the free lift must be regarded as approximate. An increase in these free-lift values of up to 75 per cent in heavy precipitation or icey conditions may be necessary. A precise knowledge of the ascent velocity is necessary only with pilot-balloon and cloud-ceiling observations, provided an assumed value for the ascent velocity is used in the calculations.

12.5.4 Change in the ascent velocity of the balloon with height

The conventional pilot-balloon observation is based on the assumption of a constant ascent velocity. A theoretical estimation of the change of ascent velocity with height can be obtained as follows:

If the initial, steady-state ascent velocity of the balloon is w_o, then following equation (7) the following expression for w_o can be written:

$$w_o = \frac{1}{D_o} \sqrt{\frac{8\ A_o}{\pi\ k.\rho_o}} \tag{1}$$

where all the parameters indexed by "o" are those valid near the ground. Assuming that after reaching a predetermined height the ascent velocity of the balloon becomes w, according to

$$w = \frac{1}{D} \sqrt{\frac{8.A}{\pi \cdot k.\rho}} \tag{2}$$

let us find out the ratio w/w_o.

Dividing equation (2) by equation (1) renders:

$$\frac{w}{w} = \frac{D_o}{D} \sqrt{\frac{A}{A_o}} \sqrt{\frac{k_o}{k}} \sqrt{\frac{\rho_o}{\rho}} \tag{3}$$

but to a first approximation $\sqrt{A/A_o} = 1$ and $k_o/k = 1$, therefore

$$w/w_o = (D_o/D).\sqrt{\rho_o/\rho} \tag{4}$$

Equation (4) represents the variation of the ascent velocity due to an increasing balloon diameter and a decreasing air density. If the respective balloon volumes V and V_o are introduced into equation (4), based on a constant air-mass displacement: $V.\rho = V_o.\rho_o$, the following result will be obtained:

$$w/w_o = (D_o/D)\sqrt{\rho_o/\rho} = \sqrt{(D_o/D)^2}\sqrt{(D/D_o)^3} = \sqrt{D/D_o}\sqrt{\sqrt[3]{\rho_o/\rho}} = \sqrt[6]{\rho_o/\rho} \tag{5}$$

Equation (5) is based on the assumption of constant air-mass displacement:

$$\rho_o/\rho = V/V_o = (D/D_o)^3$$

therefore

$$D/D_o = \sqrt[3]{\rho_o/\rho}$$

Theoretically-calculated changes of the ascent velocity with height are presented in the table below:

km	0	2	4	6	8	10	12	14	16	18	20	22	24	26
w/w_o	1	1.04	1.08	1.1	1.15	1.19	1.25	1.31	1.39	1.45	1.52	1.57	1.67	1.76

The actual ascent velocity of the meteorological balloon is not constant and it may differ considerably from the theoretically calculated values. Two groups of factors affect the ascent velocity of the balloon:

(a) Aerostatic factors (hydrogen diffusion, hydrogen excess pressure, temperature difference hydrogen/air);

(b) Aerodynamic factors: vertical currents in the atmosphere, deviation of the balloon shape from the spherical, rotation and somersaulting of the balloon, atmospheric turbulence.

Hydrogen diffusion through the rubber envelope of the balloon leads to a decrease in the ascent velocity. Experiments carried out on the ground give a decrease of six per cent of the balloon's lift in two hours of time. Consequently, the lift decrease during the first half hour is about one per cent. With a stretch of the balloon envelope during the ascent because of the lowered air density, the hydrogen diffusion increases.

The excess pressure of hydrogen reaches a maximum at the beginning of the inflation just before the rubber envelope begins to stretch. It then decreases slowly to a constant value, and reaches a second maximum shortly before the bursting of the balloon.

The average excess pressure rarely exceeds two millimetres of mercury but the maximum may occasionally reach ten millimetres of mercury. The excess pressure depends very much on the elastic properties of the balloon envelope material.

The effect of the temperature difference (temperature of hydrogen/temperature of the air) affects the lift according to the expression:

$$A = A_o + m \frac{T_1 - T}{T}$$

where:

A_o = balloon lift near the ground;

m = weight of balloon, gas and additional load;

T_1 = temperature of the hydrogen (K);

T = temperature of the air (K).

Where $T_1 - T = 10$ K, the resulting change of lift is about 1 m s^{-1}.

Up-currents and down-currents either of a convective nature or near mountains can drastically change the ascent velocity of the balloon, sometimes even making it negative.

The variations in the value of the drag-coefficient arising from changes in the shape of the balloon also affect the ascent velocity.

The results of an experimental study on the variations of the ascent velocity have been compared with the theoretical calculations and the results are demonstrated in Figure 150. The levelling-off of the experimental curve above the 15 km mark is probably owing to a puncture in the balloon envelope and a resulting temporary neutral buoyancy.

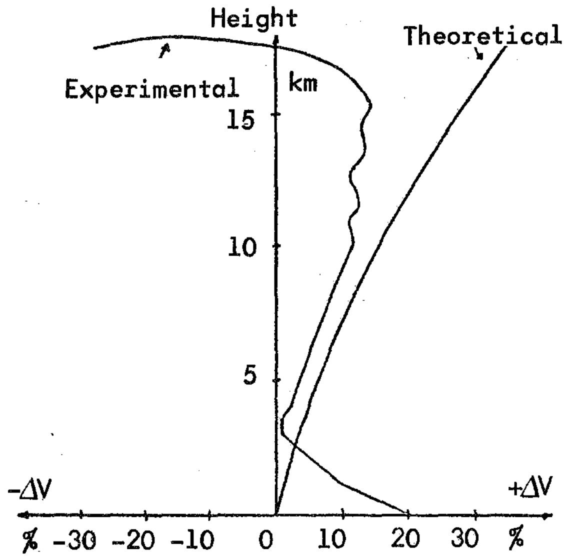


Figure 150 - Variation in balloon-ascent velocity

12.5.5 The pilot-balloon theodolite

The theodolite is an optical instrument, having a magnification of 20 to 40 times, used in the measurement of angular co-ordinates (elevation and azimuth) of distant objects. The instrument used for upper-wind measurements is known as a pilot-balloon theodolite and is slightly different in construction, permitting easy observation of the balloon near or at the zenith from the place of observation. For this purpose, the telescope of the instrument has an optical axis bent at right angles.

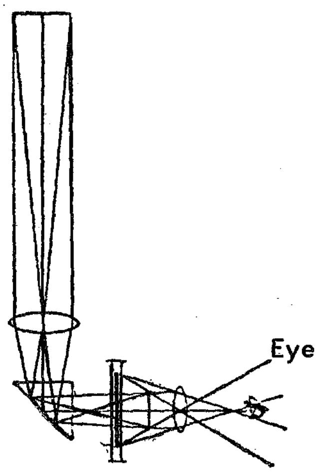


Figure 151 - Optical system of a pibal theodolite

This arrangement (Figure 151) enables the eye of the observer to remain always in the same horizontal plane, irrespective of the position of the observed balloon. An optical prism achieves the bending of the light beam. A cross-hair device inside the ocular tube helps in the exact pinpointing of the balloon whose angular co-ordinates are read against the azimuth and elevation dials with an accuracy of 0.1° (vernier provided dials). The remainder of the theodolite is a metal frame supporting the mechanism for rotation of the viewing tube about vertical and horizontal axes. The metal frame carries levelling screws and a spirit level used to level the instrument before use on top of a retractable tripod. Mainly three types of pibal theodolite are in use at present: angular co-ordinates read-out instruments, print-out instrument (Figure 152, the Molchanov type) and balloon-path projection recording instruments (Figure 152, the Zeiss theodolite). All pibal theodolites are provided with a wide-angle view-finder making the initial pick-up of the balloon easier, while its visual dimensions are too large to be observed through the optical tube.

A reading of the angular co-ordinates of the pilot balloon is taken every minute. An alarm clock attached to the tripod of the instrument is set to give a warning signal at the 55th second of each minute and a read-out signal every minute. At the sound of the warning signal the image of the balloon is picked-up in the middle of the cross-hairs; at the sound of the read-out signal, azimuth and elevation are read-out (printed out or punched).

The sets of angular co-ordinates, together with the corresponding values of the balloon heights (based on assumptions for a known and constant ascent velocity) are used in the evaluation of the pibal ascent through a graphical plotter (A-30).

The Zeiss pibal theodolite is provided with a balloon trajectory projection punch recording device, leaving a punched trace of tracking points on a paper disk in a known scale. A special ruler is used in the evaluation of the punched records.

A small (50 - 150 mW) radio transmitter suspended underneath the balloon enables the balloon to be tracked by means of a radio receiver with a highly directive antenna (a radiotheodolite). The method of conical scan of the antenna is used in order to achieve a tracking accuracy of 0.1° in both azimuth and elevation.

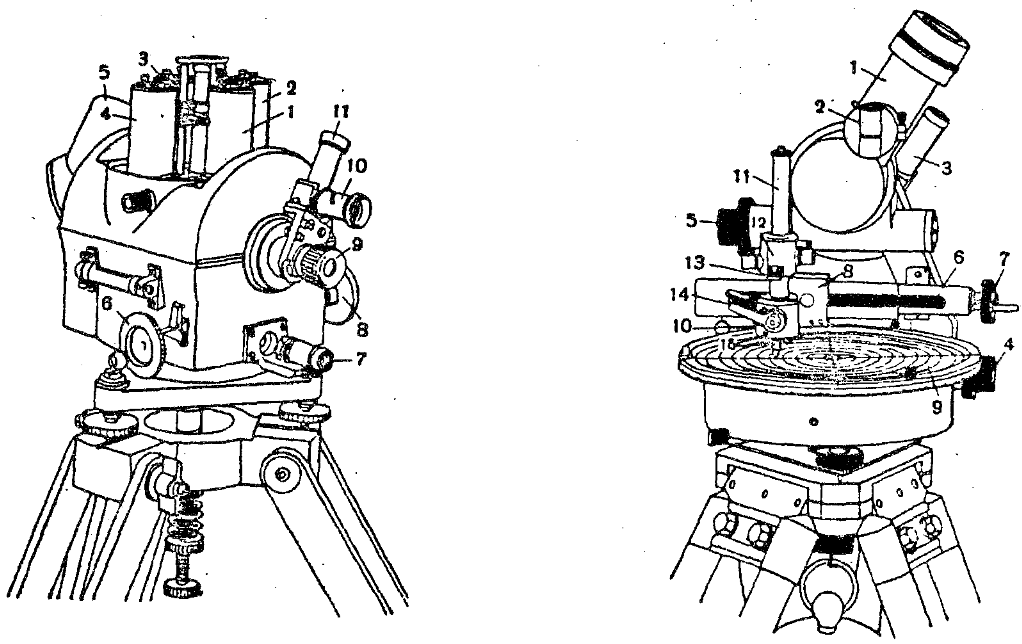


Figure 152 - Pibal theodolites

(a) Moichanov recording theodolite:
1, 2, 3, 4 = drums for angle records;
5 = objective of the viewing tube;
6 = micrometer screw of the vertical circle; 7 = magnifier for reading;
8 = micrometer screw of the horizontal limb; 9 = ocular of the viewing tube;
10 = ocular of the view finder;
11 = objective of the view finder;

(b) Zeiss recording theodolite:
1 = viewing tube; 2 = transfer lever;
3 = view finder; 4, 5 = micrometer scews;
6 = lead screw; 7 = handwheel; 8 = lead nut; 9 = paper for drawing the projection of the pilot balloon; 10 = socket;
11 = column; 12 = ring; 13 = adjusting screw; 14 = level; 15 = needle

The radio-transmitter is usually the radio link of a radiosonde with the ground station. The measurement of the atmospheric pressure at the various tracking points of the balloon enables the calculation of the actual height of the balloon, which adds to the accuracy of the upper-wind measurement.

A better accuracy in the measurement of upper-wind parameters is attained through radar observations of the flying balloon. In order to make the balloon "visible" to the radar a passive reflector (known as a corner reflector) or an active reflector (a radio receiver-transmitter known as transponder) must be suspended from the balloon.

An upper-wind sounding system based on the use of the VLF global navigation grid is specially suited for observation from moving platforms (ships). The system is used at fixed upper-air stations too.

The evaluation of the radar-wind is made using plotters based on the slant-range trigonometric equation.

CHAPTER 13

RADIOSOUNDING OF THE UPPER ATMOSPHERE

13.1 General - units of measurement

The radiosonde and related ground equipment is a measuring system for direct, remote measurement of atmospheric parameters. The routinely-measured parameters are temperature, humidity and atmospheric pressure. With the use of a radiotheodolite or radar, the components of the upper-wind may also be obtained. Radiosondes are also used for special-purpose measurements of atmospheric ozone, radioactivity, electrical potential of the atmosphere, etc.

In respect to the ceiling of the radiosonde measurement, the radiosounding systems may be bracketed into three different categories: (a) planetary-layer radiosounding systems for routine measurements within the 0 - 2 500 m height interval; (b) radiosounding systems for probing the troposphere and lower stratosphere up to 30 km; and (c) mesospheric radiosounding systems (using rockets as transport vehicles) for probing the atmospheric layers between 30 and 90 km.

The units of measurement in routine radiosounding observations are the hectopascal for pressure, the degree Celsius for temperature and percentage for relative humidity. The unit of geopotential is the geopotential metre (gpm).

Accuracy requirements as regards radiosounding measurements differ, depending on whether measurements are carried out in the planetary layer or higher. Determination of temperature with an accuracy of 0.25° in the 0 - 2 500 m atmospheric layer, humidity with five per cent and atmospheric pressure with one hectopascal will be satisfactory for most purposes.

The frequency allocation concerning sounding equipment is as follows: 27.5 - 28 MHz; 153 - 154 MHz; 400.15 - 406 MHz and 1 668.4 - 1 700 Mhz.

13.2 Principle of the radiosounding system

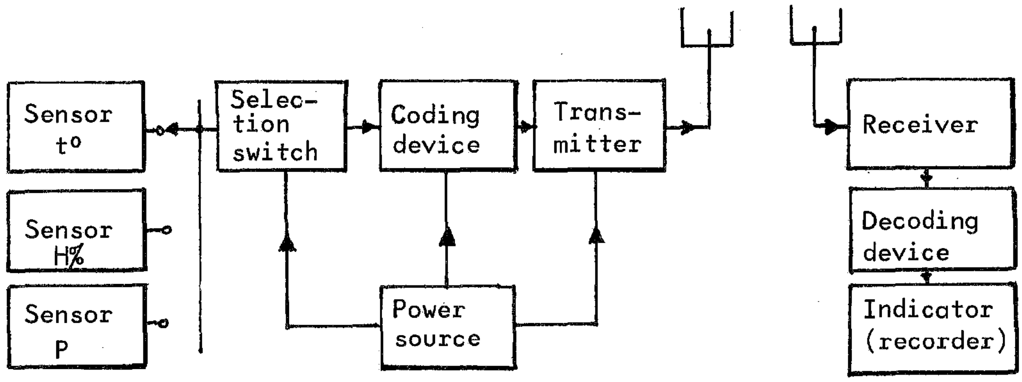
As already mentioned, the radiosounding system is a remote measuring system for direct measurements (the sensors are at the point of measurement). The general block diagram of the radiosounding system is presented in Figure 153.

A number of sensors are in use for the purposes of upper-air measurements at present. As this discussion is limited to the radiosounding equipment used for measurements in the planetary layer only, mention is made of only a few of those having a more general use:

(a) Temperature sensors: thermistors (exponential response), thermistor combination (linear response);

(b) Humidity sensors: thermistor wet- and dry-thermometer psychrometer, gold-beater's skin hygrometer;

(c) Pressure sensors: aneroid capsule.



(a) Radiosonde

(b) Ground equipment

Figure 153 - Block diagram of a radiosonde system

Radiosondes differ mainly in the coding principles used. Generally speaking, there are three principles of coding meteorological information regarding radiosondes:

(a) Morse-type coding

A coding principle used in radiosondes with mechanical sensors mainly: the values of the measured parameters are converted into combinations of dots and dashes, beamed as radio signals by the radiosonde transmitter.

Reception of signals and their decoding on the ground is usually carried out manually or semi-automatically;

(b) Time-span coding (called chronometric or pulse counting)

The values of the measured atmospheric parameters are coded into time intervals measured between a reference signal and a working signal. The coding principle is called chronometric because it involves a mechanical chronometric principle of converting measured parameters into time intervals and the synchronous working of radiosonde coding and ground-station decoding mechanisms. An alternative modification of the principle is based on the breaking down of the coding time interval into a number of pulses (signals), which are counted on the ground and thus decoded.

Fully automatic reception of the time coded information is possible;

(c) Frequency coding

Two alternatives are practicable:

(i) Carrier frequency shift coding: the measured parameter values are converted into proportional carrier-frequency shifts measured at the ground station and thus decoded;

(ii) Audio frequency coding: the measured parameter values are converted into audio-frequency values, which are measured at the ground station and thus decoded. The process is readily automated;

The coding principle (ii) is used in a number of radiosondes of all three categories of equipment mentioned above. A planetary layer radiosonde block diagram based on this principle is shown in Figure 154.

The sensors of the radiosonde presented in Figure 154 are of the resistance-type or have a sensor-parameter-into-resistance signal converter. They are switched into the circuit of a free-running multivibrator by a multivibrator-controlled semiconductor (no mechanical contact relay) switch. The frequency of the free-running multivibrator depends on the value of the sensor's resistance, which in turn depends on the measured parameter.

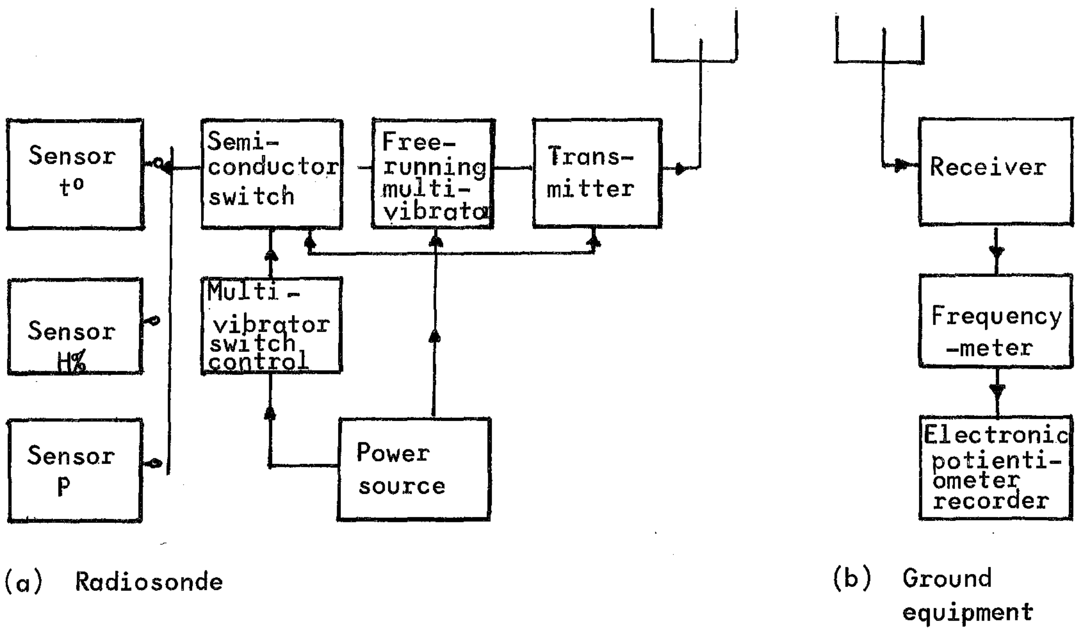


Figure 154 - Block diagram of a specific planetary-layer radiosonde system

The free-running multivibrator coding device modulates the carrier frequency of the transmitter.

The ground equipment receiver picks up the radiosonde signals and amplifies them to the necessary level, applying them to the input of a frequency-meter. At the output of the frequency-meter a voltage or current signal appears, which is proportional to the input frequency and is a function of the measured parameter (not necessarily linear). The output signal is recorded versus time by the electronic potentiometer recorder.

13.3 Principle of the radiosounding ascent evaluation

Radiosondes are not absolute measuring instruments. Because of this, they are checked for the validity of their calibration curves before ascent. At the launching site, the radiosonde is exposed to the atmospheric parameters in a ventilated screen, a procedure known as ground data lock-in. The radiosonde is then released, suspended from a meteorological balloon in free flight, and its decoded signals for temperature, humidity and pressure (eventually, wind speed and direction) recorded against the time co-ordinate.

The processing and evaluation of the radiosonde records is based on the use of the well-known barometric formula:

$$H_{1,2} = 18\,402 \log \left(\frac{P_1}{P_2}\right)(1 + 0.00366t_m)\left(1 + 0.378\frac{e_m}{P_m}\right)(1 + 0.0026 \cos 2\varphi)(1 + 1.9 \times 10^{-7}z)$$

where:

$H_{1,2}$ = thickness of atmospheric layer between pressure levels P_1, P_2;

t_m = $(t_1 + t_2)/2$ - average temperature of the layer;

e_m = $(e_1 + e_2)/2$ - average water-vapour pressure of the layer;

P_m = $(P_1 + P_2)/2$ - average pressure of the layer;

φ = geographical latitude of the place;

z = average height of the layer.

The evaluation procedures are carried out in the following steps:

(1) Determination of the linear segments of temperature along the temperature graph (temperature-graph segments between significant points of temperature, i.e. beginning and end of inversions, drastic change of gradient);

(2) Synchronization of significant points of temperature with the respective points on the graphs of pressure and humidity; tabulating the sets of parameters resulting from the synchronization;

(3) Determination of the mid-point values (the averages) of temperature, pressure and humidity, for the layers delineated by the linear segments of temperature;

(4) Application of the barometric formula for each layer and calculation of all $H_{i,j}$. Correction for height, z, namely $(1 + 1.9 \cdot 10^{-7} . z)$ may be neglected, as having no significance in the planetary layer;

(5) Using the $H_{i,j}$ points, plotting the graph height versus time on the record-sheet of the ascent.

Routine radiosounding ascents carried out to greater heights are usually corrected for lag and radiation errors before the evaluation procedures.

Sources of error in radiosounding measurements are:

(a) Change of calibration charcateristics of the radiosonde (translation or rotation of curves, or both);

(b) Ground data lock-in errors;

(c) Calculation errors;

(d) Lag errors: the temperature error $(t - \theta) = \frac{d\theta}{dz} \cdot \frac{dz}{d\tau} \cdot \lambda_v$ where t = radiosonde temperature reading; θ = actual ambient temperature; $d\theta/dz$ = actual temperature gradient; $dz/d\tau$ = ascent velocity of the radiosonde; λ_v = radiosonde temperature sensor lag-coefficient at the actual ascent velocity;

(e) Radiation error: temperature error $(t - \theta) = \frac{Q}{a}$, where Q = rate of absorption of radiation heat by the radiosonde temperature sensor; a = convective heat-exchange coefficient valid for the sensor.

CHAPTER 14

COUNTING OF LIGHTNING FLASHES

14.1 Nature of lightning - purpose of flash-counting

In fine weather, the atmosphere carries a net positive charge, implying a corresponding negative charge on the ground. It is customary to assign zero electrical potential to the ground. Measurements of the electrical potential of the atmosphere indicate that it increases with height. As a result, in fair-weather regions, the potential difference between Earth and the highly-conducting ionized atmospheric layers at about 50 km and more is hundreds of thousands of volts. This bears a resemblance to a huge capacitor. The average value of this Earth/atmosphere capacitor's charge is roughly estimated at 580 000 coulombs.

The atmospheric charge carriers (ions) move in accordance with the direction of the atmospheric electrical field and their own sign, thus creating a current assumed to be about 1 580 amperes over the entire fair-weather region of the globe. Having in mind the total-charge figure and the total-current figure, a simple calculation would show that if the atmospheric electrical field is not sustained in any way, it would be anihilated by the current in less than half an hour!

The mechanism of supporting the atmospheric electrical field is based on thunderstorm activity. The atmospheric electrical field is a process - not a condition of the atmosphere - and is sustained through the "thunderstorm-generator" principle illustrated in Figure 155.

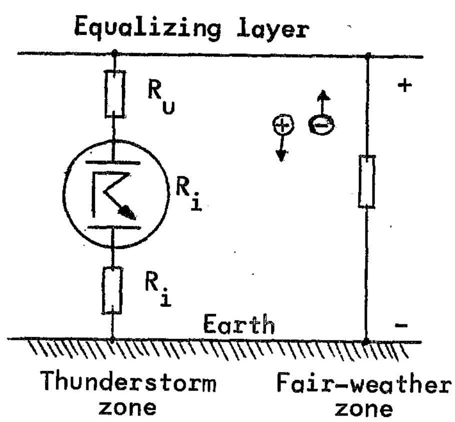


Figure 155 - The thunderstorm-generator principle

An estimated 1 800 thunderstorms are occurring simultaneously over the globe with an average "upward" current of 0.8 A. The high-conductivity ionized atmospheric layers above 50 km can be considered as a conductor equalizing the thunderstorm and fair-weather regions' currents.

The equalizing layer and the Earth's surface can be considered as a spherical capacitor with the thunderstorm generator creating a voltage difference of several hundred kilo-volts over the thunderstorm region and the fair-weather region, "drawing" an average of 1 600 A.

The thunderstorm convective clouds are the electrical generators producing electrical charges of both polarities with typical distribution and convective electrical currents. The charge-forming mechanism is attributed to a number of effects (the waterfall effect and the Mason-Latham effect among others).

The rate of change of potential with heights is called the potential gradient. The fair-weather potential gradient near the Earth's surface is about 150 V m^{-1}. Potential gradient is increased in haze, fog or cloud. Potential gradients in clear air and normal density of 3 x 10^6 V m^{-1} are called critical. They may cause an air electrical break-down, an electrical spark or lightning. Critical potential gradient in the pressure of water droplets may drop as low as 1 x 10^6 V m^{-1} initiating inter-cloud lightning. The overall field strength within a thunder cloud is about 10^5 V m^{-1}. The intense potential gradients needed for a lightning discharge are produced within the cloud in its (electrically) most active parts.

Lightning discharges are considered as two main types: discharges to ground and cloud (air) discharges. Flashes to ground, usually bringing a negative charge, may have one or several (up to 14) component strokes. The mechanism of the lightning flash to the ground is considered to have the following stages:

(1) The negative cloud charge moves toward the Earth in steps 10 - 80 m long, faintly luminous, with stops between the steps of 20 - 90 ms, leaving an ionized path behind. This is the so-called "stepped leader" having an average speed of 10^6 - 10^7 cm s^{-1}, a channel diameter of 1 - 10 m and being strongly branched because of positive charge pockets brought upwards by the convection;

(2) On reaching the ground, the stepped leader is followed by a surge of positive charge along the ionized stepped leader path from the Earth's surface to the cloud. This is the "return stroke" possessing an average speed of 10^8 - 10^9 cm s^{-1}, a channel diameter of 16 - 20 cm (owing to the magnetic pinch effect), being intensely luminous and accompanied by sound and heat effects;

(3) A second discharge to Earth along the ionized channel of the return stroke may follow (not later than 100 ms, time necessary for full recombination). This is the "dart leader". It usually has no branches and its average velocity is about 10^8 cm s^{-1};

(4) A second return stroke may follow, etc.

The electrical field connected to a moving charge (the lightning) has three components:

$$E = E_s + E_i + E_r$$

where:

E_s = the electrostatic component, dominant in the near zone and fading out in inverse proportion to the third power of the distance;

E_i = induction or magnetic component, dominant in the near zone and fading out in inverse proportion to the second power of the distance;

E_r = radiation component, dominant in the far zone and fading out in inverse proportion to the first power of distance.

The frequency spectrum of the lightning discharge covers a wide range of frequencies, from 10 Hz to more than 10 MHz. Cloud-to-ground and inter-cloud discharges differ in frequency spectra. The maximum radiation for cloud-to-ground discharges is found to be between 1 and 20 kHz.

The information concerning the number of near-zone (up to 100 km) lightning discharges is beneficial to the following five main fields of human activity:

(a) Weather forecasting, as a measure for the intensity and tendency of evolution of weather disturbances, connected with electrical activity;

(b) Aviation, as a criterion of flying hazards connected with flying in adverse weather conditions;

(c) Telecommunications, as a measure of background radio noise affecting wireless links;

(d) Electrical power transmission, as a criterion of line-voltage surge hazards and necessity of counter measures;

(e) Hail-suppression activities, as a statistical entity entering the ratio hailstorms/thunderstorms to be used in the evaluation of the suppression effect.

14.2 The Sullivan-Wells lightning-flash counter

The Sullivan-Wells lightning-flash counter is an instrument used in the statistical estimation of the frequency of thunderstorms over a small area of up to 100 km radius. Its block diagram is shown in Figure 156. The signal from cloud-to-ground discharges is picked up by the 7 m rod-antenna and is delivered to an aperiodic filter passing the frequency band between 1 kHz and 20 kHz (half-power points). This is the frequency band in which the maximum radiation on energy of the cloud-to-ground discharge lies. The frequency response curve of the counter is shown in Figure 157.

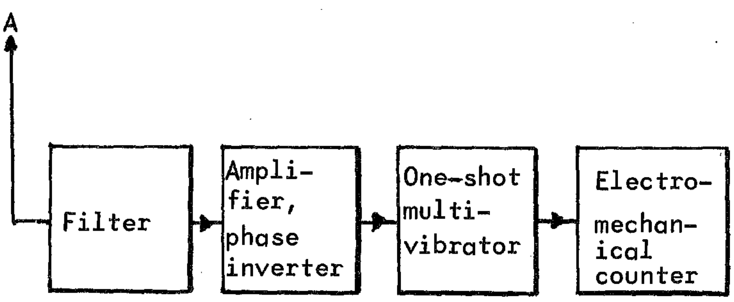


Figure 156 - Block diagram of a Sullivan-Wells lightning-flash counter (LFC)

From the filter, the signal is passed on to the amplifier, the second stage of which acts as a phase inverter, providing a positive output pulse irrespective of the polarity of the input. The positive pulse triggers the one-shot multivibrator, which drives the mechanical counter, counting the lightning discharges. The time constant of the instrument is selected to be 0.25 s, which enables the counting of multiple strokes as one.

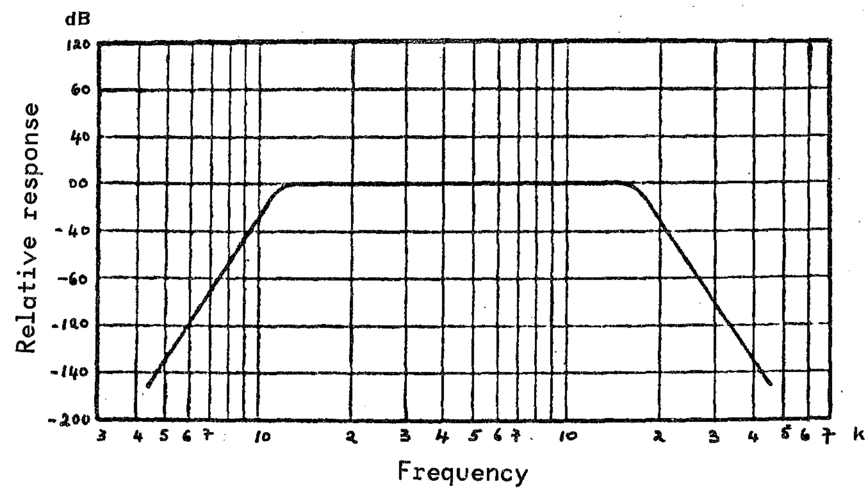


Figure 157 - Frequency response of Sullivan-Wells LFC

The actual wiring diagram is presented in Figure 158. The amplifier is built around the two halves of the first 6SN7 and the multivibrator is built around the second 6SN7 tube (see Part III). The press-button switch, S, provides a facility for the injection of a calibration pulse of a desired amplitude between 0 and 6 V. The response of the lightning-flash counter to a given signal amplitude determines its range. The range calibration curve is presented in Figure 159.

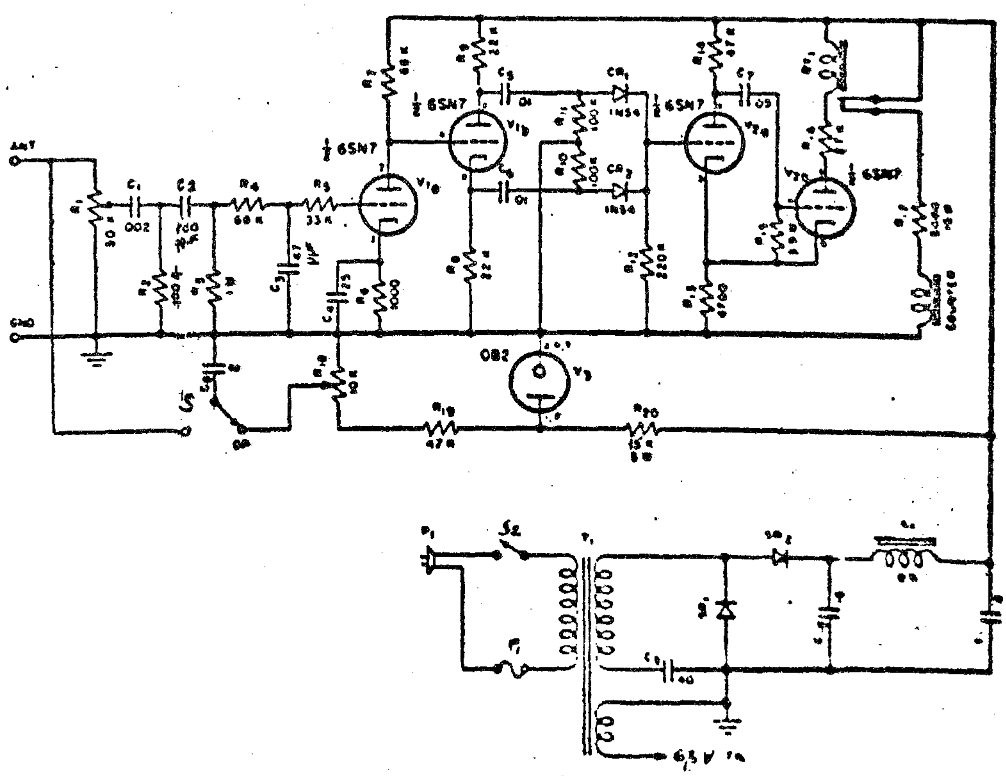


Figure 158 - Wiring diagram of Sullivan-Wells LFC

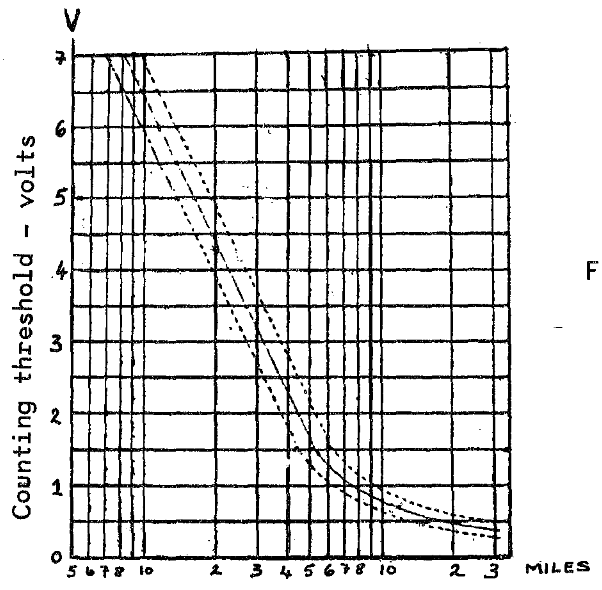


Figure 159 - Calibration curve for range of Sullivan-Wells lightning-flash counter (LFC)

It should be borne in mind that with the actual current strength distribution in the lightning, close, weak lightning discharges would give the same effect as distant, strong ones. Nevertheless, a range can be defined for the lightning-flash counter and it has been found through experience (parallel radar measurements) that the signal threshold values (threshold of sensitivity of the counter) 1 V, 1.6 V, 3 V and 5.6 V correspond to the ranges 160 km, 80 km, 50 km and 20 km.

An experimental curve is shown in Figure 159 drawn in a semi-logarithmic scale with the threshold voltage along the ordinate and the range in miles along the abscissa. The accuracy claimed by the definition of the maximum range of the lightning flash counter is ± 15%.

The VLF frequency band has been chosen for lightning-flash counting not only because it contains the maximum of radiated energy but also because it contains a minimum of man-made radio noise.

14.3 The transistorized lightning-flash counter

Following the recommendation of the World Meteorological Organization for a global study of thunderstorm activity, a number of different types of lightning-flash counter have been designed and put into operation in the various Member countries. The modern trend toward solid-state electronics has affected the design of the instruments.

One transistorized version of the WMO-recommended Sullivan-Wells lightning-flash counter is shown in Figure 160 - the Gallo-Mezösi instrument.

Like the electron-tube version, this instrument picks up the lightning-stroke signals through a rod antenna, which passes them on to the amplifier and phase inverter T_1 through an aperiodic filter. The amplitude of the signal is limited by a pair of Zener diodes.

The signal is further fed into the input of an emitter follower, T_2, which triggers a one-shot multivibrator based on the transistors T_3, T_4. The multivibrator, which has a time constant of 0.25 s drives the T_5 power stage with the electromechanical counter in its collector circuit.

The circuit diagram shown in Figure 160 is, in fact, one channel of a five-channel instrument, the sensitivities of the different channels being set to the threshold voltages 1 V, 1.6 V, 3 V and 5.6 V, corresponding to the ranges 160 km, 80 km, 50 km and 20 km. This arrangement enables a more accurate estimation of the range of the thunderstorm source of the lightning-stroke signals.

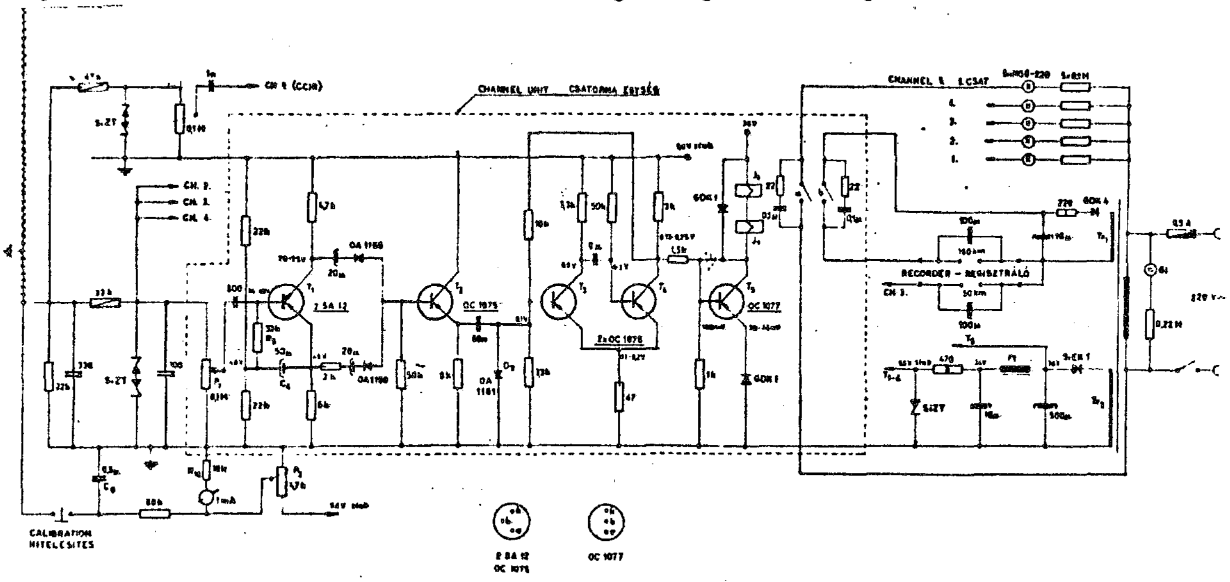


Figure 160 - Galo-Mezosi transistorized lightning-flash counter (LFC)

14.4 Installation and siting of lightning-flash counters

The performance of lightning-flash counters is affected by the presence at close proximity of large grounded metallic masses (underground pipes, metal towers, etc.). Their sensitivity must be standardized and checked at least once a week, using the built-in step-voltage calibrator. The height of the antenna, as well as the length of the feeder cable are subject to accepted standards.

A suitable installation site is a plot of land away from iron structures and underground piping. A small pavilion is the best place for the installation of the instrument.

14.5 Routine maintenance of lightning-flash counters

If battery operated, lightning-flash counters should be checked regularly in regard to source voltage.

Every day, after reading out the counter, a calibrating impulse should be injected by means of the push button, thus checking the performance of the mechanical counter, as well as the instrument's calibration.

Recording instruments should be checked routinely, regarding their paper-feed and recording mechanisms.

CHAPTER 15

AUTOMATION OF THE MEASUREMENT OF METEOROLOGICAL VARIABLES

15.1 Technical and economic aspects of automation - objectives

The measurement of atmospheric variables, which is part of the meteorological observation, is in essence a physical measurement. In the meteorological network, consisting of manned meteorological stations, it is the human operator who takes an active part in the measurement process.

With the present state of development of electronic engineering and technology, the human observer could be substituted in some cases partially and in others totally by a machine. Meteorological equipment capable of providing information on the atmospheric variables without the participation of a human observer is called automatic equipment. Such equipment, which can take over and carry on the routine observation activities of the human observer at a meteorological station, with or without control by a human operator, is known as an automatic weather station (AWS). Automatic weather stations can be used individually or organized in an automatic meteorological network.

The beginnings of automation in meteorology can be traced back to the early 1940s when the first attempts to acquire data automatically from remote and inaccessible parts of the globe (the Arctic) and at sea were made.

Automatic data acquisition should provide a cheaper source of data of comparable quality to those obtained manually for operational and scientific purposes. If not cheaper, it should provide a means of data acquisition which would be difficult or even impossible to attain manually in terms of quality, speed or obtaining meteorological data from uninhabited areas.

This outline of the objectives of automation shows that there is an economic aspect which should be taken into account. Studies of the economical benefits of the automation of meteorological data acquisition have been carried out in a number of highly industrialized countries. The results reveal a long-term economic benefit, which becomes obvious when considered over a 10-year interval.

Cost-to-benefit studies of automation applied to meteorology are of a complicated nature, involving a number of factors specific to the country of application.

Approached from a technical point of view, there are only a few observational routines of the manual meteorological observation which have not yet been automated satisfactorily (one such being the observation of the character of the cloud cover).

Since the beginning, automation in meteorology has acquired an ever-increasing technical sophistication. The first AWS were electromechanical devices having limited data-acquisition and transmission potential. They have been succeeded by electronic AWS of the "hard-wired" type, more powerful in their information capabilities, but working according to programs pre-determined in their design.

Later generations of AWS have been greatly improved in sampling techniques, data pre-processing, storage and dissemination.

Present-day AWS, microprocessor- and microcomputer-based and software-controlled, are highly flexible, large information-output machines, far ahead of the manual system in speed and quality.

The microcomputer may perform a number of specific tasks in an AWS, including:

- Control of peripheral devices (radio, analogue-to-digital converters, interfaces for event counting, etc.);
- Timekeeping;
- Processing of received messages (parity checks, checksum, receiver address, format and action code);
- Processing of sensor data (sampling, averaging, solving data discontinuities, etc.);
- Generating and sending coded data messages.

Contrary to hard-wired logic, which is dedicated to specific tasks and is non-programmable, the computer approach, through proper software development, enables the AWS to adapt to a wide variety of users' needs.

15.2 Classification of automatic weather stations

The question of classification of the AWS can be approached from various standpoints. It has become customary to bracket AWS into two main classes according to the purpose for which their information output is used:

(a) Climatological AWS (non-real-time or régime-data AWS);

(b) Synoptic AWS (real-time data AWS).

Representative equipment from both categories may be totally alike except for the presence of a coding unit and a telecommunication link in the real-time AWS, connecting the station with the consumer of the real-time information output. A telecommunication unit is not necessarily a part of the climatological AWS.

The two main classes of AWS as defined above may be further subdivided. Depending on the kind of installation site, automatic equipment may be specified as "on-land" (urban, desert, mountain) or "oceanic" (ship-board, drifting buoy, anchored buoy).

AWS can be classified according to the intended use of their information output: aviation, adverse-weather warning, pollution monitoring, microclimatology, etc.

Technical characteristics of automatic equipment may be taken as a basis for classification: mains-powered, battery-powered, generator-powered, mechanical weather stations, fully electronic, on-site or off-site data processing, environmentally protected or unprotected (for indoor installation), etc.

A classification of AWS exists based on the information potential of the equipment, starting with the simple five-variable data logger as the lowest category.

Different classes of automatic equipment may be considered based on the reliability characteristics of the AWS, etc., etc.

A great diversity of automatic equipment marks the development of the AWS at present. A need for standardization of the performance requirements for AWS is recognized.

15.3 Basic block diagram of an automatic weather station

A block diagram presentation of the automatic meteorological station covering all possible kinds of existing equipment would be too general to be of any practical value for the explanation of its principles. A simplified representation of a typical climatological station of the automatic type is illustrated in block form in Figure 161.

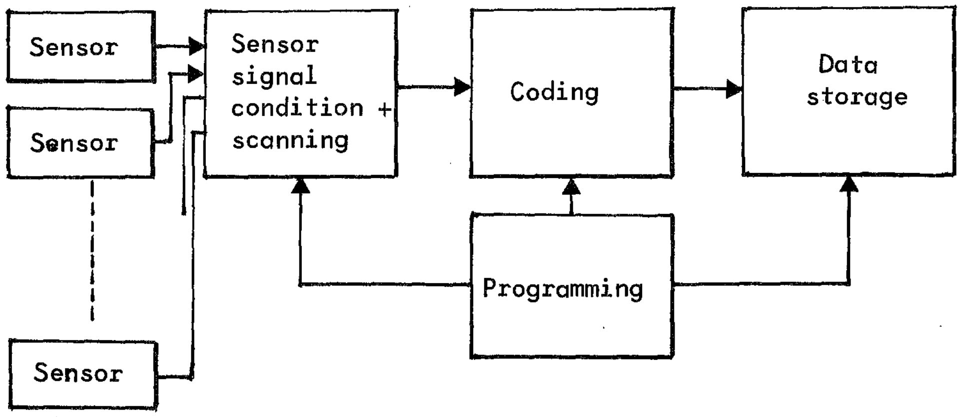


Figure 161 - Block diagram of a climatological automatic weather station

The sensor block contains all the AWS sensors with their respective adapters and signal conditioners, as well as the sensors' sequential scanning device.

The coding device converts each sensor's conditioned signal into a coded message, part of the accepted format, and passes it on to the data-storage unit. The coded information is stored on a suitable storage medium (often magnetic tape).

In order to read the stored information, either a special read-out device is used, decoding it and presenting it into an alphanumerical form or, if the code is computer compatible, the information can be obtained at its peripheral devices in the desired form.

The programming device actuated by a programming clock, controls the timing of the measurement cycle of the AWS and the work of all its units.

The block diagram would be a little more complicated if it were to show a climatological AWS connected to a collecting centre by a land-line. Usually a telegraph-line and a teleprinter are favoured for such purposes.

Even when the use of electronic AWS becomes operational, often as part of an automatic meteorological data-acquisition system, simple robust mechanical meteorological stations will remain in use and in production. One such AWS is pictured in Figure 162 which records on paper in analogue form the following five weather variables: temperature, humidity, precipitation, wind speed and wind direction. The 27 cm strip-chart moves at a rate of 0.5 - 1 cm h^{-1}. All the station's sensors are of the mechanical type and the period of unattended operation is two months.

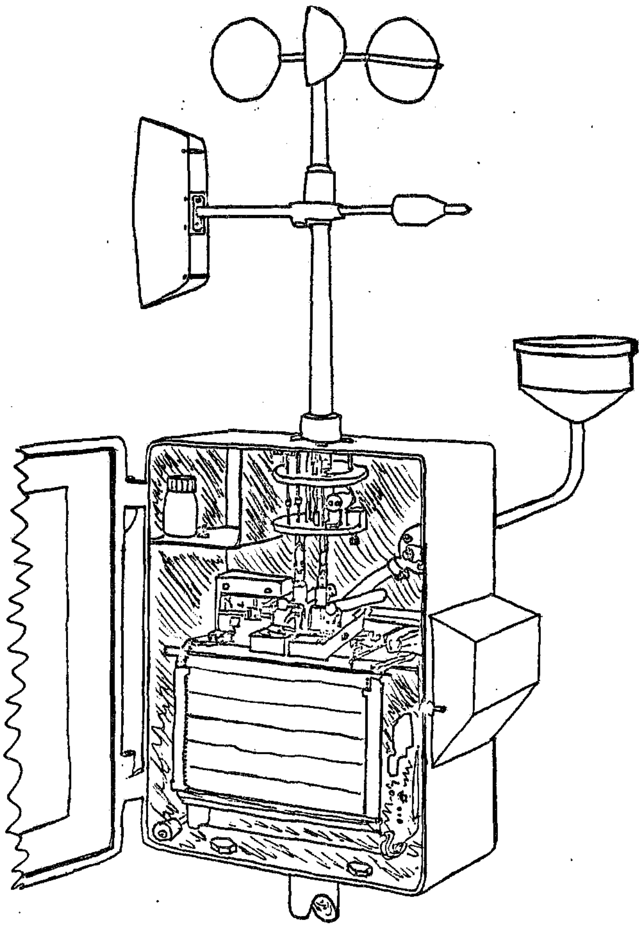


Figure 162 - Mechanical automatic weather station (AWS)

A contemporary microcomputer-based, mesoscale logging-data AWS is shown in Figure 163. The remote AWS samples the local sensors synchronously and transmits the data via a 400 MHz radio-link to the base-station at one-minute intervals. There the data are immediately available for real-time use and are recorded on magnetic tape for later analysis.

The remote AWS samples the temperature, humidity, wind speed and direction, rain and pressure at one-second intervals, averaging the data and storing them in the local memory in a message format with special identification and validity-check characters.

When a command is received from the base-station, the remote AWS turns on its transmitter and sends the data message. If the base station detects an error in the message, it will request re-transmission; remote stations will store messages for possible re-transmission. The remote AWS operates its transmission facility for short intervals of time in order to save energy. The station is battery-operated.

The collecting (base-station) centre fulfils the following three functions:

(a) Data logging: the data flow from the receiver is directed to the computer for additional processing and conversion of physical units, and then to industry-compatible magnetic-tape units. A file of recent data is maintained on either tape or disk;

(b) Data-quality assurance: the stream of data from each sensor is examined to ascertain data quality. Graphic cathode-ray tubes (CRT) are used to display questionable data sequences. A hard-copy device records the CRT display;

(c) Real-time data analysis: using the disk file of recently-recorded data and the graphic CRT displays, the operator can monitor the data. Hard copies are made for additional data-quality assurance.

The sensors used at the remote AWS are partly event sensors (wind speed: cupwheel/light-chopper; precipitation: tipping bucket) and partly analogue sensors (temperature: resistance thermometer; wind direction: wind vane/three-tap potentiometer, etc.).

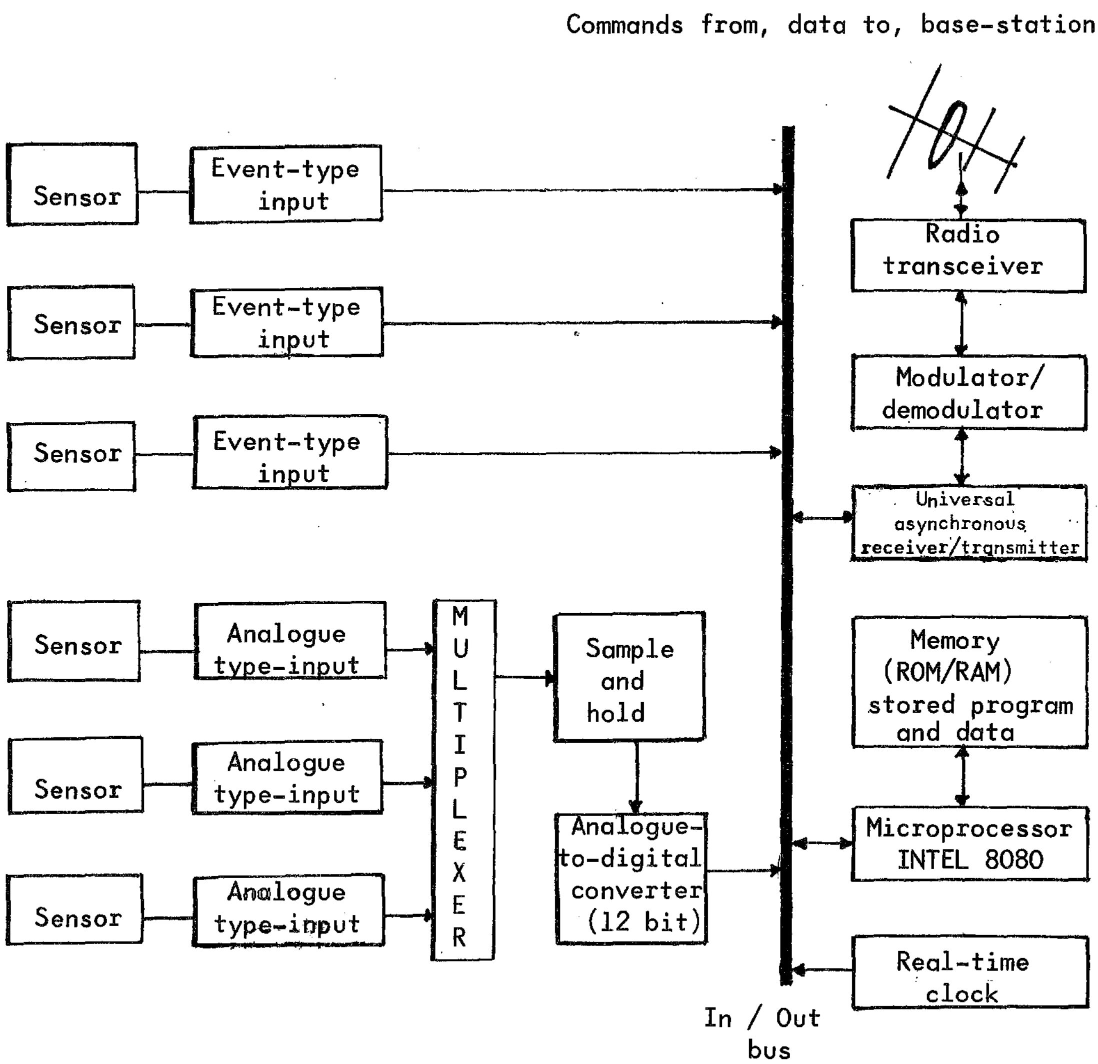


Figure 163 — Block-diagram of a portable automated mesonet (PAM) AWS

The analogue inputs are provided with instrumentation amplifiers (high impedance, floating, differential input; gain selectable from 1 to 1 000; output bias from -5 to +5 V), filters to minimize spectral aliasing by the 1 Hz sampling rate. The analogue outputs are connected to an eight-channel multiplexer, a sample-and-hold amplifier and a 12-bit analogue-to-digital converter.

The signal from the event sensors is shaped by Schmitt triggers and the pulses are counted by 12-bit counters, provided with an optional divide-by-N overflow protection stage. The event sensor input card can handle event signals having amplitudes in the range 1 - 10 V. The event outputs are processed further by the electronic package of the AWS.

The telecommunication link is a radio working in the meteorological telemetry band of 400 MHz. A modem interfaces the data stream to a dedicated telephone line.

The remote station, as well as the base-station have a modular design.

15.4 Sensors used with automatic weather stations

The earliest AWS types, many of them having electromechanical sensor scanning, were equipped with mechanical sensors: bimetallic thermometer, hair hygrometer, aneroid-capsule barometer, tipping-bucket precipitation sensor, etc. Some of these sensors still have their use even in computer-based AWS designs.

The sensor's suitability for use with automatic equipment may be decided from the consideration of two sets of sensor features:

(a) The sensor's functional features, i.e. accuracy, stability of calibration characteristics, specificity of response and durability;

(b) The sensor's automatic equipment coupling features: event or analogue output, atmospheric-parameter-to-sensor algorithm, easy exchangeability, low maintenance requirements, low power requirements.

Generally, event-output sensors are preferred for use in automatic equipment based on digital techniques. The analogue sensors need complicated adaptors and analogue-to-digital converters. Because of the lack of event sensors for measurement of some meteorological variables, the AWS use both types.

With the increased sampling rate of modern automatic equipment, the lag-coefficients of the sensors used have become important.

Very few new sensors have appeared in a "ready-for-automation" form for application purposes since the beginning of the AWS era.

15.5 Maintenance of automatic weather stations

Maintenance varies, according to the type of automatic equipment, its purpose and site.

AWS sited at places with difficult access (generally speaking, these are seasonally inaccessible sites) are subjected to checks and overhauls at suitable intervals of time. Catastrophic failures or drift failures of the equipment during periods of inaccessibility are simply not treated. In some cases, equipment may be replaced and the faulty equipment serviced in the workshop, as is usually the case with drifting or anchored buoys carrying an AWS.

Different maintenance approaches are used as regards attended and unattended automatic equipment: with an attended AWS, it is usually the operator on shift who takes care of the current maintenance and a mobile repair crew take care of a number of repairs; unattended equipment is usually serviced by a centrally-based mobile repair squad.

The following sensors, ranked in a priority order, are used in AWS:

Measured parameter	Sensor type
Temperature	• Platinum resistance thermometer • Thermistor, linear response • Thermistor, exponential response • Bimetallic thermometer
Humidity	• LiCl dewcel • Thermistor psychrometer • Hair hygrometer • Pernix-hygrometer
Atmospheric pressure Wind speed	• Aneroid capsule • Mercury barometer • Cup-wheel sensor • Propellor sensor
Wind direction	• Wind vane
Precipitation	• Tipping bucket • Valve volumetric chamber • Weighing balance
Sunshine duration	• Photocell sensor • Thermistor sensor
Solar radiation	• Thermopile
Luminance detector	• Photocell
Precipitation detector	• Electrical resistance sensor • Electrical capacitance sensor
Cloud ceiling	• Rotating-beam ceilometer
Visibility	• Transmissometer • Back-scatter visibility meter

Current maintenance, as well as on-site repairs are facilitated by the modular design of automatic equipment. Specialized equipment is used for the sensors' calibration tests on the site and some AWS have analogue outputs for this purpose.

Sensor adapters are usually designed to enable quick adjustment following an exchange.

Maintenance and repair techniques and practices should match in efficiency and speed the automatic data acquisition. Discontinuities in the data-acquisition rate and prolonged, idle periods arising from failures drastically reduce the advantages to be derived from the automation of meteorological-data acquisition.

Planning the maintenance and repair work of the supporting personnel is as important as the efficient execution of the activities. Planning should be based on the reliability parameters of the equipment, as well as experience.

Accuracy requirements for automatic weather stations (synoptic)

Element	Stated accuracy requirement	Comments
Atmospheric pressure	±1.0 hPa over land ±2.0 hPa over sea	The change in error between successive 6-h observations Should not exceed ±0.5 hPa
Wind direction	±20°	
Wind speed	±2 m s^{-1} below 20 m s^{-1} ±10% above 20 m s^{-1}	
Air temperature	±1 °C	
Sea temperature	±1 °C	
Dew-point temperature	±1 °C for dew-point deficit below 4°C ±2 °C for dew-point deficit above 4°C	
Precipitation (accumulated amounts)	±0.5 mm below 5 mm ±10% above 5 mm ±2 mm below 10 mm ±20% above 10 mm	Over land Over sea
Visibility	±20% below 4 km	
Cloud-base height	±20% below 600 m	
State of sea (height of waves)	±1 m below 10 m ±10% above 10 m	
Geographical location (when varying)	±1° latitude	Valid for drifting buoys; supposed to be determined by editing station.

15.6 Reliability of automatic equipment

The term reliability used in connexion with machines and equipment has the meaning of a probabilistic characteristic of a machine or equipment concerning the expectancy for continuous work without failure or change of performance features. A reliability figure expressed in per cent and having a value of 100, meaning that the equipment in question will never fail, can never be achieved. Equipment designers strive, however, to reach the highest possible reliability figures, taking into account economic considerations and the consequences of a failure.

An indication of the reliability of a piece of equipment can be obtained by a simple experiment, i.e. testing a number of the equipment types for prolonged periods of time and keeping track of the failures but this is a rather costly and inefficient method.

Each type of equipment consists of components and it goes without saying that the reliability of the equipment depends on the reliability of the components used in its design. It is feasible to assess the reliability of a piece of equipment through the reliability figures of its components. Let us consider briefly the question of reliability of a component (this may be any kind of component, from rivets and bolts to capacitors, resistors, etc.).

If we have a number, N_o, of similar components to be tested for reliability and after a test period, $\Delta N = N_o - N$ have failed, we may define the probability for satisfactory performance of the component under test (its reliability) as follows:

$$P(t) = \frac{N}{N_o} \tag{1}$$

In such a case, the probability for a failure could be expressed as

$$Q(t) = 1 - P(1) \tag{2}$$

We can define a parameter λ as a "failure rate" for the component or a change of reliability with time by the following expression:

$$\lambda = \frac{dP(t)}{dt} = \frac{1}{N} \cdot \frac{\Delta N}{\Delta t} \tag{3}$$

The theory gives a time dependency of λ illustrated in Figure 164.

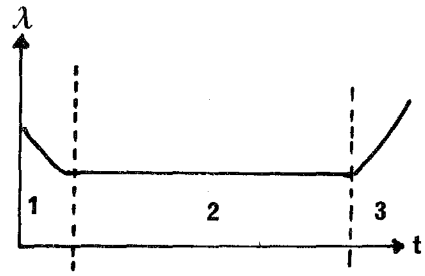


Figure 164 — Failure rate, λ,

Three distinctly-marked zones on the graph are recognizable: (1) zone of the inborn defects (debugging); (2) zone of random defects; (3) zone of wear-out defects. For the zone of random defects (constant failure rate) an expression for the change of the tested components' number with time is obtained in the form:

$$N = N_o e^{-\lambda t} \tag{4}$$

Taking into account (1) an expression for the reliability is obtained from (4) in the form

$$P(t) = e^{-\lambda t} \tag{5}$$

Another useful reliability parameter is the so-called "mean time between failures" (MTBF), which could be deduced from (4). A general expression for MTBF is the following:

$$MTBF = \frac{t_1 + t_2 + \dots + t_n}{N_o} \tag{6}$$

where:

t_i = time of operation of one element until failure;

N_o = number of elements.

Through integration from equation (4) is obtained:

$$MTBF = \frac{1}{\lambda} \tag{7}$$

The equipment could be considered as consisting of i different kinds of components, n elements of each kind, the reliability of each kind of component being $P_i(t)$.

If all the important components of the equipment are considered as being connected in series, the failure of one of them would cause the failure of the equipment. For such a case, the equivalent reliability of the equipment, P_{eq}, would be a function of $P_i(t)$, taking into account the number, n, of each kind of component:

$$P_{eq} = P_1^n \cdot P_2^{n2} \cdot \dots \cdot P_i^{ni} \tag{8}$$

Substituting $P_i(t)$ from (5) gives:

$$P_{eq} = e^{-(n_1\lambda_1 + n_2\lambda_2 + \dots + n_i\lambda_i)} \tag{9}$$

and

$$MTBF = \frac{1}{(n_1\lambda_1 + n_2\lambda_2 + \dots + n_i\lambda_i)} \tag{10}$$

Expressions (9) and (10) can be used in the calculation of the reliability parameters of the equipment, provided the reliability parameters of the corresponding components are known.

The reliability parameter failure rate, λ , as given by the component manufacturers, is given in the table below:

The failure rate, λ , $\left(\frac{\text{failures}}{\text{elements/h}}\right)$ for different electronic components

Component	λ	Component	λ
Resistors (composition)	1.10°	Relays	20.10^{-6}
Resistors (film)	3.10^{-6}	Tubes	80.10^{-6}
Capacitors (mica)	3.10^{-6}	Transistors	$7 + 40.10^{-6}$
Capacitors (paper)	10.10^{-6}	Diodes	$1 + 40.10^{-6}$
Capacitors (electrolytic)	30.10^{-6}	Potentiometers	200.10^{-6}
Capacitors (ceramic)	1.10^{-6}	Transformers	$50 + 200.10^{-6}$

Example of estimation of reliability parameters

Let us find the MTBF and the time for secure work by a fixed reliability of an APT receiver consisting of the following components:

Component	Number	Failure rate	Total failure rate
Resistors	900	1.10^{-6}	9.10^{-4}
Capacitors	500	3.10^{-6}	15.10^{-4}
Diodes	30	10.10^{-6}	3.10^{-4}
Transformers	10	50.10^{-6}	5.10^{-4}
Transistors	50	10.10^{-6}	5.10^{-4}
Potentiometers	10	200.10^{-6}	20.10^{-4}
			$\lambda_{eq} = 57.10^{-4}$ failures/h

$$\text{MTBF} = \frac{1}{\lambda_{eq}} = 175 \text{ h}$$

The reliability figure of the equipment (probability of survival) would be:

$$P(t) = e^{-t/\text{MTBF}}$$

Re-arranging and taking logarithms on both sides gives:

$$t = \text{MTBF}.\ln\left(\frac{1}{P(t)}\right).$$

Fixing the probability of survival at 0.95, the time t would be:

$$t = 175 \ln (1/0.95) = 9 \text{ h}.$$

The above figure for t means that in 95 out of 100 cases the equipment would still work, but would fail after 175 h.

With $P(t) = 0.90$, t would be 17.5 h.

Using military-specification components may increase t by 10 - 100 times.

PART 2

METEOROLOGICAL INSTRUMENT MAINTENANCE WORKSHOPS, CALIBRATION LABORATORIES AND ROUTINES

INTRODUCTION

Operational meteorology greatly depends on the comparability of meteorological measurements carried out routinely over the entire area covered by the observing network of stations. To obtain satisfactory comparability, the following two major requirements have to be fulfilled:

(a) A standard approach to measurement practices;

(b) Preservation of the required operational state of the meteorological instruments involved in the measurement routines.

The meteorological inspection takes care of the fulfillment of prerequisite (a), its activities being aimed at attaining the strict observance of existing standards of measurement practice by the network personnel.

The meteorological instrument maintenance workshops (MIMWs) and calibration laboratories take care of prerequisite (b). In their instrument maintenance and calibration activities, the technical personnel of workshops and laboratories are assisted by the local station personnel, who carry out routinely the simpler maintenance operations such as cleaning, replenishing ink, changing recording charts, checking instrument accuracy, etc.

The meteorological instrument maintenance workshops and calibration laboratories are usually branches or departments of the Meteorological Services and handle the technical problems connected with the instruments and equipment.

The following main objectives are considered as inherently "instrumental and technical" and are assigned to the instrument departments of the Meteorological Services as follows:

(a) To the MIMW:

- Installation and current maintenance of the stations' facilities and equipment;
- Installation and current maintenance of meteorological instruments;
- Repair of existing and design of new meteorological instruments and equipment;

(b) To the meteorological instrument calibration laboratories (MICLs) - laboratory- and field-testing of meteorological instruments and equipment:

- Routine care of meteorological standard instruments and laboratory equipment;
- Development of new calibration and testing methods and meteorological control of newly-introduced meteorological instruments.

As far as the priorities of these objectives are concerned, those aimed at securing the required technical/operational level of the meteorological observations have the highest priority. Second priority is assigned to the research and development activities of MIMWs and MICLs.

CHAPTER 16

METEOROLOGICAL INSTRUMENT MAINTENANCE WORKSHOP ACTIVITIES

16.1 Installation and maintenance of station facilities and equipment

The establishment of new, ordinary meteorological stations entails a number of technical activities of a special nature: installation of wind-measuring masts, meteorological shelters, various instrument stands and measuring sites, remoting cables, power installations, etc. Diverse technical skills are required of the technical personnel for the job to be done well and efficiently. Even greater knowledge and skills may be needed in the installation of upper-air, agrometeorological and airport meteorological equipment.

While the participation of the local station's personnel in these activities is unavoidable and contracted skilled local labour may be of great help, the competent guidance and control of the installation procedures by MIMW staff is indispensable. In fact, in all cases of installation of specialized equipment such as upper-air and airport meteorological equipment, the use of MIMW installation crews seems to be the right policy.

It pays to keep a meticulous log of all technical procedures in connexion with the technical operations of the instruments' and equipment's installation. The records could be of value later in the planning of current maintenance and repair activities.

Subject to local arrangements and standing regulations, complex pieces of station equipment may be maintained by local maintenance crews, as is often the case with upper-air stations, for example. Irrespective of the availability of local maintenance crews and especially for major equipment failures, MIMW maintenance crews of superior experience may be despatched to the field station. Such trips are conveniently used in the local maintenance personnel's training activities as well.

16.2 Installation and maintenance of meteorological instruments

Most of the ordinary meteorological station's instruments (thermometers, hygrometers, etc.) are sent to the station by post, the necessary care being taken over packing and handling while in transport. The observer himself establishes these instruments on the site, checking the newly exposed instrument against a similar one of a higher accuracy rating.

It is generally safer for some of the conventional meteorological instruments, like mercury barometers, to be brought to outlying stations rather than sent. Their establishment on the site is quite simple provided the specific rules are observed and may also be accomplished by any well-trained observer.

The installation and commissioning (as well as testing in the field) of one class of instruments, however, requires considerable knowledge and technical skill normally not in the possession of rank-and-file observers and should be carried out by the MIMW staff. Among these figure different remote-reading instruments, for example, the electrical remote-reading anemograph, temperature- and humidity-gradient remoting equipment, solar-radiation remote-reading instruments, etc.

Besides field maintenance, laboratory and workshop maintenance of meteorological instruments belong within the range of activities of MIMW technical personnel. As already indicated, ordinary meteorological instruments are periodically sent to the MIMW to be cleaned, oiled, calibrated or re-adjusted, according to the maintenance schedules or needs.

If done regularly, all current maintenance cycles constitute an appreciable workload on the MIMW. These activities are the back-bone of operational meteorology and their scheduled execution contributes decisively to the accuracy of meteorological measurements and hence to the increased efficiency of Meteorological Services.

16.3 Repair of existing and design of new meteorological instruments and equipment

Repair of meteorological instruments is another important field of activity of the MIMW. A small number of instruments, glass thermometers among them, are simply discarded if broken. Most meteorological instruments and equipment are usually repaired if damaged.

Generally, MIMW will handle all kinds of repair :

(a) Mechanical (wood, plastic, metal) instrument repair;

(b) Electrical repairs, including cabling and wiring;

(c) Electronic, tube and solid-state instrument repair.

The range of repair work will depend on the engineering and technological level of the instruments and equipment involved, as well as the technical potential of the MIMW. The basic requirements as regards the technical potential of an MIMW, below which its support renders itself non-economical, is a technical level enabling repairs of conventional meteorological station instruments plus remote-reading equipment. Existence of an adequate component stock-pile is assumed.

An average MIMW should be capable of doing all kinds of mechanical repair using available materials and spares. In some cases, such an MIMW should be capable of producing the needed spare parts itself, using materials available locally and eventually resorting at times to the services of outside organizations better equipped for the purpose. The same should apply to electrical and electronic repairs.

With the diversity of meteorological instruments which at present exists, a completely self-sufficient MIMW, capable of handling all repair cases by itself, would be difficult to achieve. Such an MIMW would have to be very well instrumented and equipped and its personnel in possession of very broad and high-level professional qualifications. An MIMW like this could readily cope with an additional objective, i.e. manufacture in a limited number of some conventional meteorological instruments accessories, e.g. (in order of complexity) stands for Campbell-Stokes sunshine recorders, 10-m anemograph masts and guy-wire assembly, meteorological shelters, evaporation pans, etc.) as well as the development and design of new meteorological instruments for special research purposes.

It is impractical to give a description of how wide the scope of repair work of an MIMW should be, since much depends on the local conditions in which the

MIMW is functioning. When all components have to be imported, the re-winding of a selsyn motor, for example, may be considered worthwhile, whereas with locally-made spares in the conditions of an industrialized country, such a repair may be considered a sheer waste of time and effort.

In any case, the problem of the maintenance scope must be approached giving due consideration first to its meteorological operational aspects and then to its economical aspects. Repairs to meteorological instruments always appear urgent and spares are always needed. Spare parts, on the other hand, especially imported ones, can be translated directly into financial terms. This means that the stock-pile of spares should be well-balanced and the failure rates of the various instruments' components considered. An extreme example to better illustrate the point is that it would be wrong to keep in stock hundreds of permanent magnet anemometer rotors with a life expectancy comparable to that of the basic equipment (10 years), whilst having only a few dozen toggle switches, subject to a failure rate with the same equipment of once a month.

16.4 General approach to the assessment of the instrument maintenance and repair workload

The question of the assessment of the instrument maintenance and repair workload may come under consideration in connexion with either the establishment of new MIMW facilities or with already-established facilities for the purpose of planning the technical activities in that field.

The total maintenance and repair workload may be thought of as consisting of the following components:

(a) Current maintenance of instruments, equipment and facilities;

(b) Installation of new instruments, renovation of existing equipment and facilities;

(c) Repair of damaged instruments, equipment and facilities.

The current maintenance component can be assessed, based on the relevant WMO technical norms (Guide to Meteorological Instruments and Methods of Observation (WMO-No. 8)), as well as professional experience. The table below gives an idea of the periodicity of the various maintenance procedures concerning certain meteorological instruments and equipment. It is a rule of thumb but, nevertheless, a practical one, to find the workload in man-months concerning this component, based on the knowledge of the time necessary for the various procedures and their total number. Allowance should be made for the transportation time of round trips of maintenance personnel.

The installation and renovation workload component can be assessed based on experience. The use of the following statistically-backed formula may give better results in the evaluation of the different tasks, than the intuitive approach:

$$w = \frac{a + 4m + b}{6} \quad (w,\ a,\ b,\ m \text{ in } h \text{ or } d)$$

where:

w = average duration of the task;
a = pessimistic expectation for the duration of the task;

b = optimistic expectation for the duration of the task;

m = the expectation for the most probable duration of the task.

The repair component of the workload is the most difficult to assess because of the probabilistic nature of the instrument and equipment failure. An allowance can be made for this component based on existing reliability figures of the equipment, if such figures are available.

In the long run, a methodically kept record of instrument and equipment failures may prove to be of considerable value in this respect. With failure rates available, an allowance should be made in the direction of an overestimation of the workload, on the assumption of an increase of failure rate with time due to wear-out.

Current maintenance

No.	Instrument, equipment, facility	Lab. or MIMW	Field	Checks/ comparison	Adjustment	Periodical mechanical maintenance	Periodical electrical maintenance	Frequency (years/ months)
1	Meteorological screen		x			Fix/paint		1/2y
2	Instrument stands		x			Fix/paint		1/2y
3	Anemometer masts		x			Fix/paint		1/2y
4	Mercury barometers							
	. Working standard against primary standard A	x		Comparison				1/2y
	. Reference standard C against national working standard B	x		Comparison				1/2y
	. Station barometer S with reference standard C		x	Comparison				1/1y
5	Aneroid barometer/recorder		x	Comparison	Adjustment	Clock		1/1y
6	Thermometer - glass	x		Ice-point				1/5y
7	Thermometer - metal resistance		x	check	Drift			1/1y
8	Thermometer - thermistor		x	2 point	Drift			1/6m
9	Thermographs	x		N point	Scale	Clock		1/1y
10	Hygrometer - organic	x		2 point	Scale	Paint		1/1y
11	Dewcel (LiCL)		x	2 point		Fix/paint	Wiring	1/6m
12	Hygrographs - organic	x		N point	Scale	Paint/clean		1/1y
13	Psychrometers		x	Comparison		Change wick		1/2y
14	Recorder - clockwork	x			Speed	Clean/oil		1/2y
15	Anemometers - electrical	x		N point		Oiling	Wiring	1/5y
16	Wind vane - electrical					Clean/oil	Wiring	1/10y
17	Precipitation recorder		x			Clean/oil		1/2y
18	Evaporation pans		x			Clean/paint		1/2y
19	Lake evaporation pans		x			Clean/paint		1/6m
20	Solarimeter, radiometer	x		CST check		Paint	Wiring	1/2y
21	Solarigraph (Robitch)	x		CST check		Clock		1/2y
22	Sunshine recorder		x			Fix/clean		1/1y
23	Evapotranspirometer		x			Fix/clean		1/6m
24	Transmissometer		x	Optical check		Paint	Projector	1/1y
25	Ceilograph (RRC)		x	Optical alignment		Paint	Projector	1/1y
26	Radiotheodolites		x	Optical/electrical check			Recording parameters	1/1y
27	Hydrogen generator		x	Safety valve		Paint		1/1y
28	Gas cylinders			Pressure		Paint		1/1y

16.5 Layout of workshop and storage space

Workshops and storage space should be as close as possible to each other, so that transportation of materials, tools and spares from, as well as storage items to, the stores does not involve more time and effort than is necessary.

Because workshops tend to be noisy, it is better to site them away from the administration and scientific-research buildings.

The nature of the work requires that materials and equipment are brought in and out, activities which are easier if there are no stairs to climb. In this respect, if workshops have to be accommodated in a large building shared by other units, it is better to have them on the ground floor or, alternatively, in the basement (provided easy access via a drive-in ramp is available).

The accommodation of the workshops in a specially-built, one-storey building, of standard architecture, offers a number of advantages, the most important being that all units of the "instrument department" (i.e. workshops, laboratories and stores which are functionally connected to each other) can be brought to the same place and arranged in the most suitable way. Other advantages are connected with the movement of materials and personnel, lighting, heating and power installations, etc.

If new instrument-department facilities are planned, the functional relationships between different workshops, laboratories and stores should first be analysed. This analysis is based on the movement of materials between the different units and depends largely on the scope and scale of intended activities. A block diagram of the functional relationships between facility units is presented in Figure 165

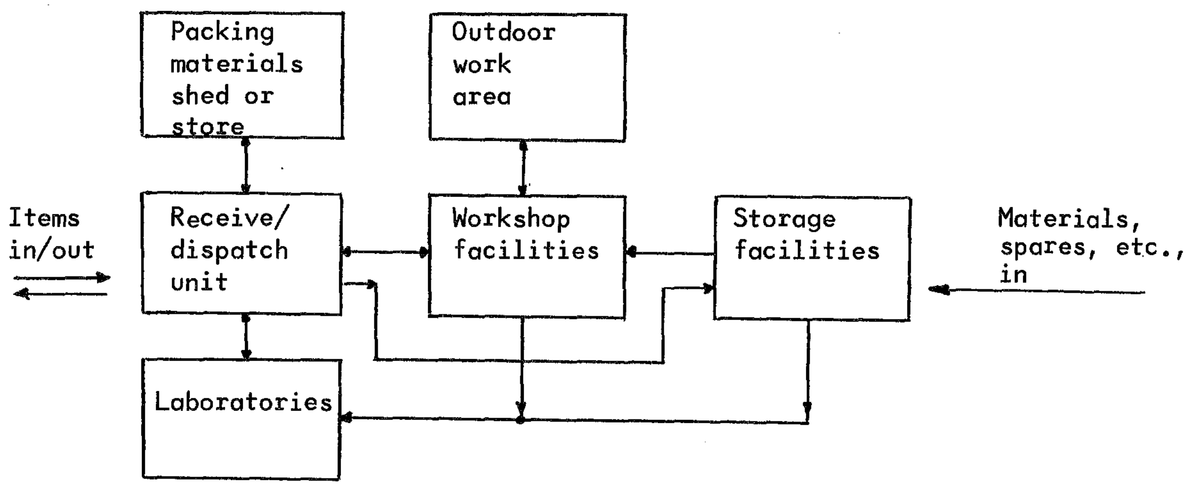


Figure 165 - Block diagram of relationship(s) between units

All instruments subject to current maintenance and repair sent from the field stations are re-directed through the "receive/dispatch" unit to either the workshops (for repair, cleaning, oiling, etc.) or to laboratories (for comparison, check and calibration.)

The spare parts necessary for the repair, as well as materials used in current maintenance come to the workshops from the stores. The box indicating generally the stores represents all the different storage units (bulk materials, expendables, spares, tools, etc.) which are usually accommodated in separate rooms.

The instruments and equipment repaired or subjected to current maintenance in the workshops either go directly to "dispatch" to be returned to the field station concerned or through the laboratories for calibration and testing and then through dispatch to the field station in question. Serviced instruments may be returned to the stores through dispatch.

Alternative optimum workshop and laboratory space layouts can be derived from this functional diagram. As already mentioned, the area to be covered by the different units depends on the scale and scope of technical activities planned and is determined according to the machine and equipment space, manipulation space and transportation space requirements.

Figure 166 shows an example of the layout of the workshops and laboratories of an instrument department (standard workshop architecture assumed).

The territorial requirements, as indicated in each of the boxes representing separate workshop and laboratory units, are those of an average instrument department. Office space necessary for the professionals is assumed to be in a different building if a one-storey workshop-compound design is assumed. The only office inside the workshop building is that of the workshop superintendant.

With the exception of the mercury laboratory, all workshop and laboratory units are accessible from the inside of the building in order to facilitate movement of personnel and materials. The painting/drying space, carpenter's workshop and mechanical workshop are also accessible from outside through the outdoor working area. Large objects, equipment and materials are brought in and out of these workshop units through the outdoor working area. (The mercury laboratory is accessible only from outside, so as to prevent the spread of toxic mercury throughout the coumpound.)

The acetylene gas generator necessary for the torch-welder is accommodated in a separate bunker outside the coumpound for safety reasons. Water and sewage installations should be available in the gas bunker and the electrical lighting should be controlled from outside.

Materials which are not sensitive to weather (some types of wood, pipes, plastic materials, galvanized iron, etc.) are kept in an outside storage shed, fenced with wire-mesh covered by plastic roof-sheets.

The packing materials' store is also accessible from outside, thus preventing the spread of dust inside the building arising from the unloading of secondary packing materials (cardboard, used wooden crates, etc.).

An outdoor radiation-instrument exposure site used for the comparison of radiation-measuring instruments is connected by cables to the solar-radiation laboratory.

The outdoor working area next to the carpenter's shop is provided with weatherproof power outlets and is used as for assembling large structures.

Power, water and sewage requirements are considered in the following chapters in connexion with the installation of machine tools and equipment.

One important question connected with the lighting and heating considerations (discussed in section 16.6) is the orientation of the building. One advantageous

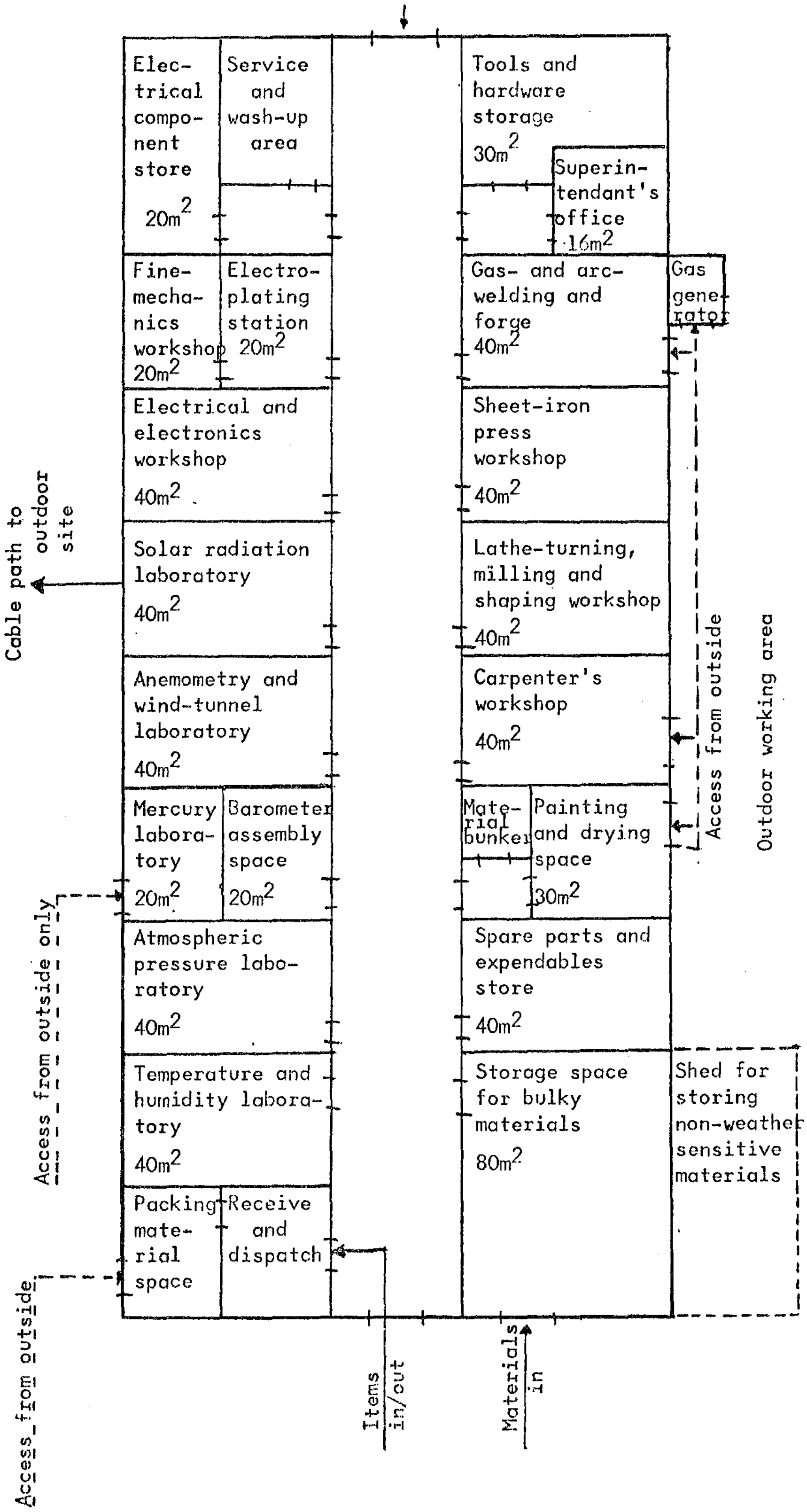


Figure 166 - Example of workshop and laboratory layout (drawing not to scale)

orientation as far as day-time lighting is concerned, is that illustrated in Figure 167(a). The building has its broadsides facing south and north.

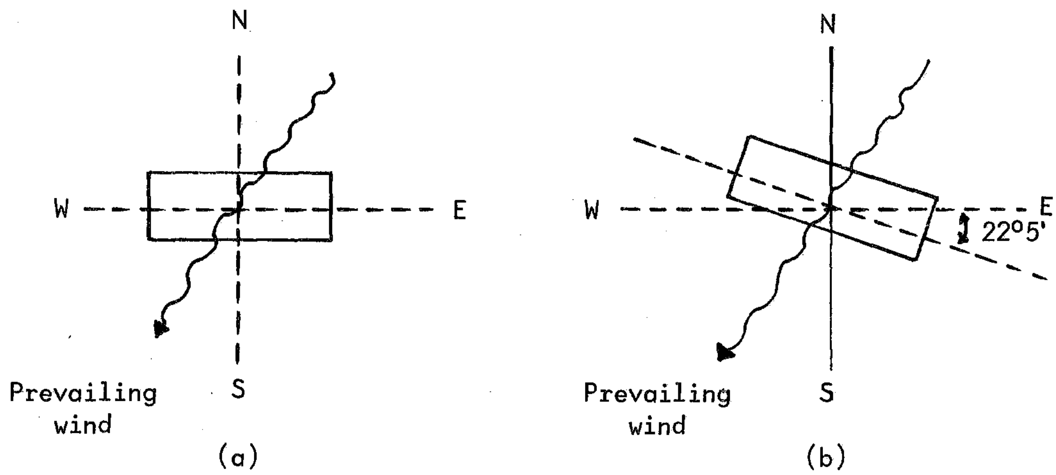


Figure 167 - Workshop- and laboratory-coumpound orientation

For heating purposes, the prevailing wind has also to be taken into account. Figure 167(b) presents a compromise solution of the building's orientation suitable for hot climates - optimum sunlight and breeze. In cold climates, exposure of the broadside to the prevailing wind should be avoided.

16.6 Lighting - heating - ventilation - acoustic insulation - safety considerations

Day-time lighting in the workshops and laboratories should be as effective as possible and, in certain climatic regions, window lighting may be supplemented by roof illumination. Overhangs must be accurately calculated to cut off direct sunrays, especially in hot climates.

Special attention should be given to the electrical lighting of the workshop and laboratory compound. The minimum lighting for the work area should be considered as being 300 lx. Task lighting should be provided at specific places: lathes, milling machines, fine mechanics bench, etc. Cold luminescent lighting has definite advantages over incandescent lamps, but luminescent tubes must be used in polarity pairs of opposite polarity in order to avoid the strobe-effect of the single-light source.

Light wall-colouring improves the luminosity of working places. The ceiling should be covered with light latex paint and walls with light oil-paints.

The mercury laboratory walls and ceiling should be painted with water-repellent, washable paints and the floor should be covered wall-to-wall by a synthetic, washable and smooth surface cover.

The walls and ceiling of the gas- and arc-welding workshop should be painted in light-absorbing dull colours to prevent reflections from the arc-light, which are harmful to the eyes of those assisting personnel who do not wear goggles.

The optimum average temperature in workshops is 18°C. Central heating is the ideal solution for medium-sized workshops, but an overhead fan-drive system is preferable for larger working areas.

No heating is required for the mercury-purification laboratory, mercury-barometer assembly station and the standard-barometer station. The presence of exposed or spilled mercury on the working tables or floor presents a hazardous source of mercury vapours in confined spaces, especially at higher temperatures.

A heating system capable of keeping an almost-constant temperature around the clock is beneficial to the room climate of workshops having large masses of metal in them (heavy machine tools). Due to human-body radiation-heat losses to the surfaces of cold metal, a feeling of discomfort is felt by workers in the early morning hours in workshops where the heating is switched off at night, despite the air temperature being 18°C.

Just as an adequate heating system is important in cold climates, a good cooling system is indispensable in hot climates. Air-conditioning in the laboratories is important not only for the comfort of the workers, but for the nature of the work as well. Adequate cooling and ventilation systems for the mercury laboratory and barometer-assembly station are essential. The ventilation ducts of the mercury-purification laboratory should be capable of aspirating air near the floor of the room and expelling it far away from the premises.

Efficient cooling and ventilation are necessary for the gas- and arc-welding workshop because of the extra heat dissipated by the welding process and because of the generation of fumes and metal vapours by the electric arc.

Noise and vibrations are unavoidable in certain workshop activities. Acoustic insulation in the form of hard-top, synthetic, foam-lined wall panelling is recommended for the sheet-metal processing workshop, carpenter's workshop and the wind-tunnel laboratory. Vibrations of the heavy machines should be damped by anchoring them in heavy cement pedestals. Reduction of the noise level in the instrument department helps to reduce the fatigue of the workers.

A dust-collecting system for the wood-processing machines is essential for healthy conditions in the carpenter's workshop.

All machine tools and equipment require either three-phase or single-phase mains voltage supplies. Overhead power outlets for these machines are favoured for security reasons. Magnetic short-circuit breakers of the necessary power rating should be installed near the respective machines. A master switch, having an ON light signal controlling the total electrical power in the workshop unit or laboratory, is recommended.

Machine tools are usually electrically zeroed, but an earthing arrangement is an additional safety measure against possibly fatal electric shocks. A good earthing system must have a fractional transitional (to earth) resistance. The earthing of lightning rods must be far away (at least 20 m) from that of the machines.

All inflammable materials should be stored in metal containers in an outside cement bunker. Small quantities of solvents and other inflammable materials can be kept in a metal cupboard in the painting and drying anteroom.

Fixe extinguishers in an operational state should be kept in conspicuous places. Short but explicit explanations as to their use should be posted near the equipment, together with the telephone number of the nearest fire-station.

Open gears and belt drives should be equipped with adequate guards for safe operation. Electrical-drive press machines and guillotine shears should be provided with safety devices preventing the machine from being set into operation involuntarily.

Safety zones should be painted around hazardous machines. In the most hazardous cases, guard-rails may be used.

Drinking water should be made available in workshops and laboratories, especially in hot, tropical climates.

16.7 Layout of machines, tools and equipment - general

A well-planned layout of machines, tools and equipment in the various workshop units is important for the efficiency of work in these units. With a reduction in the unnecessary movement of personnel and materials, a substantial economy in effort and energy can be realized.

When establishing new workshops or laboratories, the planning and layout of machines, tools and equipment is best carried out in the following three steps:

(a) Listing of the necessary machines, tools, equipment and furniture with due consideration being given to their availability on the local market, cost, transportation and installation;

(b) Calculation of the total space requirements for the various units taking into account machine- and manipulation-space requirements;

(c) Actual layout of the machine taking into account space requirements for the machines and manipulation thereof as well as movement of personnel and room for materials.

For the preliminary listing of workshop items, detailed specifications of each item are necessary:

- Dimension and weight;
- Mechanical characteristics;
- Electrical characteristics;
- Power ratings;
- Necessary accessories;
- Cost.

The specifications for a milling machine are given below as an example:

- Milling-machine length, width, height and weight;
- Table size, longitudinal travel, cross-travel, vertical travel;
- Spindle speed;
- Power feed, number of feeds, longitudinal, vertical, etc.;
- Standard equipment (arbor support, tools, lamp, manuals, etc.);
- Accessories (spindle adapters, swivelling vice, three-jaw chuck, etc.)
- Cost (of machine, transportation, installation).

Based on the specifications listed, a list of chosen items is prepared with an indication against each item of the space and power requirements. An example of the space requirements concerning different workshop items is presented in Figure 168 (solid line represents the machine dimensions, dotted line the machine-manipulation space). Following Figure 168, cardboard cut-outs of the various machine and workshop items' space requirements may be prepared to a suitable scale. The workshop-unit drawing may be conveniently used together with cut-outs of workshop items to the same scale when exploring the various layout alternatives. The workshop unit-quadrature is indicated by dots, the distance between two adjacent dots being one metre (Figure 169).

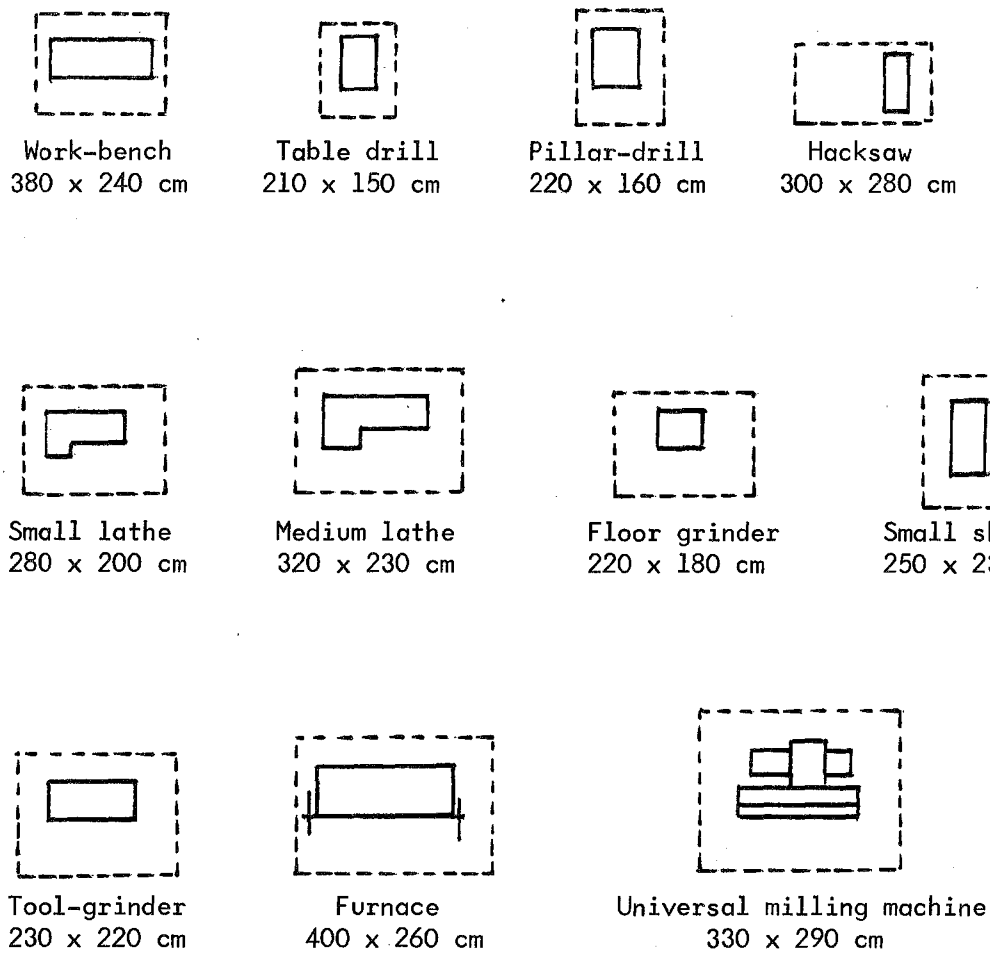


Figure 168 - Space requirements for manipulation of workshop machines (not drawn to scale)

As far as transportation space requirements are concerned, a passage between the machines wide enough for a push-trolley to pass and manoeuvre is necessary.

Water-pipes and drainage necessary for machine cooling are placed in floor grooves covered by iron plates sunk flush with the floor. Cooling water in small quantities may be brought to the machine by flexible-pressure rubber hose, the draining hose connected to the drainage system. Medium-power-rating spot-welders are cooled in this way.

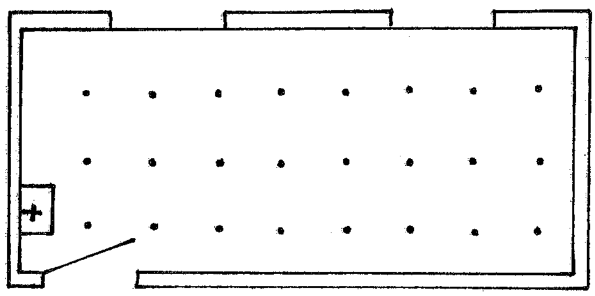


Figure 169 - Graphical approach to estimation of workshop area

The observation of the following basic principles is recommended in planning the location of the various machines and pieces of equipment:

(a) Very heavy machines should be located as near the service door as possible; they should be mounted on concrete pedestals and levelled carefully;

(b) Light and movable machine tools may be placed along the walls;

(c) High-precision machines should be located in such a way that they receive natural light throughout the day;

(d) Machines used for cutting stock to size should be located near the material store-room door;

(e) Tool-grinders should be placed near tool store-room doors;

(f) Passageways in workshops should be allowed for, bearing in mind the easy handling of small material-distribution trolleys;

(g) Forges, furnaces and welding booths should be located near an outside wall and provided with exhaust systems;

(h) Hand- and machine-tool accessories should be placed within easy reach of machine-tool operators. Tool-boards or cabinets can be used for the purpose;

(i) Machines needing extra manipulation space (like most carpentry machines) should be installed in line with the service door;

(j) Machines needing cooling water on tap (e.g. medium-power-rating spot-welders) should be located near water and drainage outlets/inlets.

Storage-space layout is designed according to the nature of the stored materials and the need for processing them. Thus, bulky and weather-insensitive materials are stored outdoors under shelter. Cables and steel wires, usually delivered wound on spools of considerable weight and size, should be stored in rooms having direct access from outside:

- Tools are stored near the workshop premises;
- Stationery is stored near the office area;
- Spares are kept in rooms near the workshops and laboratories.

The storage system must be such that quick and easy retrieval of items by the stores personnel is possible without involving more technically-qualified personnel. The specifications of the stored items must be completely listed in detail in the store files and their location clearly marked to facilitate rapid pinpointing by persons who do not necessarily know what the required item looks like.

Certain items are subject to storage requirements such as constant temperature or humidity, or both, (e.g. upper-air balloons and sondes) which warrants the installation of air-conditioning in the stores.

16.8 Workshop personnel - general - qualifications

The number of people engaged in the activities of the workshops and the qualifications required depend largely on the workload and objectives of the workshops. The lowest requirements in this respect would concern workshops taking care of current maintenance of only the conventional surface meteorological instruments of a relatively sparse meteorological network.

For the purpose of this compendium, a "professional" staff member is a university graduate in engineering or physics and a "technician" is a suitably-qualified staff member with a technical-school (or equivalent) education.

The maintenance of remote-reading electrical instruments, solar-radiation instruments, telecommunication equipment, upper-air and airport instruments and equipment, calls for the participation in the workshop activities of suitably-qualified technical personnel at all levels.

It will be realized that, in addition to the workload and scope of activities, the decision about the number and type of technical personnel needed to man the MIMW will also depend very much on the local conditions. While rigid rules in this respect would not help, a guide based on experience can be useful, as given in the table below.

With the ever-widening use in meteorology of radar, satellite ground equipment, automatic weather stations and computer-based devices, maintenance and repair become increasingly specialized. Technical fields which have branched off from electronics are already enormous areas of human knowledge, requiring specially-prepared staff and equipment in order to be able to handle maintenance and repair. It is becoming routine practice to attach to the above-mentioned instruments and equipment maintenance and repair crews consisting of technicians and professionals, who may also be acting as equipment operators.

The current maintenance and repair of radar sets require special microwave measuring equipment, which is not, generally speaking, a part of the conventional electronics workshop instrumentation, but rather that of a more sophisticated laboratory. In very much the same way, satellite ground-equipment maintenance has outgrown the telecommunication-maintenance qualification requirements and has become the task of a specialized unit. The same trend is even more evident with automatic equipment and computers. Because of the complexity of such equipment, it is more economical to carry out major repairs on a contract basis with highly specialized outside agencies, having highly qualified personnel and the necessary, expensive repair facilities.

Qualification requirements for MIMW personnel

Type of workshop (1)	Technical staff (2)	Professional staff (3)	In-service training (4)	Supervisor (5)
Fine mechanics	Technical school or equivalent	-	Up to 6 months	Technician
Electrical	Technical school or equivalent	University or equivalent - Electronic engineering; - Physics	Up to 4 months	Technician
Electronic	Technical school or equivalent	University or equivalent - Electronic engineering; - Physics	Up to 12 months	M.Sc.
Mechanical	Vocational (specialized) school	University or equivalent - Mechanical engineering	Up to 4 months	B.Sc.
Carpenter's	Vocational (specialized) school	-	Up to 3 months	Foreman
Mobile workshop	Technical school	University or equivalent - Electrical engineering	Up to 6 months	B.Sc.

As already mentioned above, arrangements with respect to maintenance and repair practices may differ from country to country, depending largely on local conditions.

16.9 The fine mechanics maintenance workshop (FMMW)

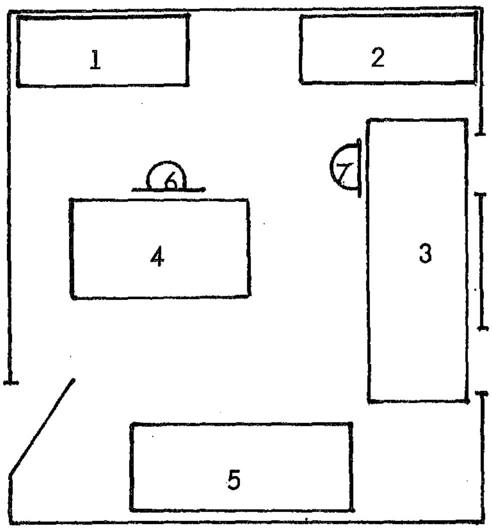
The fine mechanics maintenance workshop has as a basic objective the maintenance and repair of the clockwork and related mechanisms of recording meteorological instruments. In addition, the FMMW is expected to assume responsability for the mechanical repair of various fine mechanisms used in meteorology, such as electro-mechanical counters, gears of anemometers and aneroid barometers, etc. Occasionally, the FMMW may render assistance in the repair of equipment of other meteorological branches using, strictly speaking, non-meteorological technical means. This is often the case with mechanical repairs to telecommunication equipment.

The total workload of a FMMW may be split into two groups based on the periodicity with which it occurs. Regular or periodical activities of the FMMW cover the maintenance of the network meteorological instruments, mainly cleaning, oiling and adjustment of clockwork mechanisms. The repair work of the workshop is of a random nature, depending on the occurrence of instrument failure.

The number of technicians working for the FMMW depends on the workload. Average workshops rarely employ more than one qualified fine mechanic, who takes care of the maintenance and repair, as well as the failure statistics of instruments in his field of competence.

16.9.1 The FMMW furniture

The furniture items answering the fundamental requirements of a fine mechanics maintenance workshop are given in Figure 170.



(1) cabinet for incoming instruments;

(2) cabinet for outgoing (repaired) instruments;

(3) hard-top work-bench for the turning lathe, engraving machine, bench-top drill with accessories, vice size 3, etc.;

(4) work-bench having a protective lid and tool compartments;

(5) cabinet for materials and spares;

(6) swivel chair;

(7) swivel chair.

Figure 170 - The FMMW furniture layout (not drawn to scale)

The cabinets used containing the incoming and outgoing instruments may be ordinary office-type metal cabinets, suitably large, with doors whose upper half is of glass and drawers and ordinary doors below. An advantage is to have adjustable shelves inside the cabinets.

The hard-top bench accommodates larger pieces of fine mechanics machine-tools, certainly a turning lathe (possibly a combined one having milling and drilling attachments), possibly an engraving machine, a bench-top drill with accessories (cutting-heads holder on a flexible cable drive, small-toothed circular saw, etc.), larger vice, hand-saw, etc. The drawers of the bench contain all the necessary hand-tools and accessories of the machine-tools. An adjustable work-lamp is essential, although the position at the bench should permit excellent natural lighting conditions as well.

A work-bench with a protective lid is the permanent working place of the fine mechanic. A sturdy wooden bench may be used; a light-coloured plastic overlay for the bench top is suggested, in order to make work with small objects easier. A front edge threshold is a useful precaution to prevent miniature components rolling off.

The protective lid should be easily detachable for everyday work. Very often it is a flexible wooden lathed cover, which, guided by two rails, can be simply rolled away from the seated mechanic. This cover serves the dual purpose of preventing dust from settling on any sensitive clockwork mechanisms and accidental damage to these mechanisms by visitors or cleaning staff.

A work-lamp is necessary in such a position vis-à-vis the windows to allow natural light to fall onto the top of the bench from the left-hand side of the technician.

The cabinet for materials and spares may be of the same type as those used for keeping the incoming and outgoing instruments. Materials used in the routine work of the FMMW, mainly round and hexagonal brass, plastic and aluminium sheets, etc., are cut to stock before bringing them into the workshop. The spare parts are mostly small and should be kept in separate plastic boxes, clearly tagged for easy retrieval.

Swivel chairs are favoured in the FMMW, because they facilitate the easy movement of the mechanic, which may be necessary several times throughout a working day.

No special place is designated for the technician's daily routine of receiving the instruments for maintenance and repair nor for logging the failure statistics in this connexion.

16.9.2. The FMMW tools and equipment

A variety of watchmaker's tools and equipment is available at present on the market, the producers of such equipment offering (very often free of charge) detailed and well-illustrated catalogues. The purpose of this section is to familiarize the student of meteorological instruments with the basic tools and equipment in this field, as well as the terminology, which may be beneficial later, regardless of the direction his meteorological career subsequently takes.

One widely-used watchmaker's machine tool is the turning lathe shown in Figure 171.

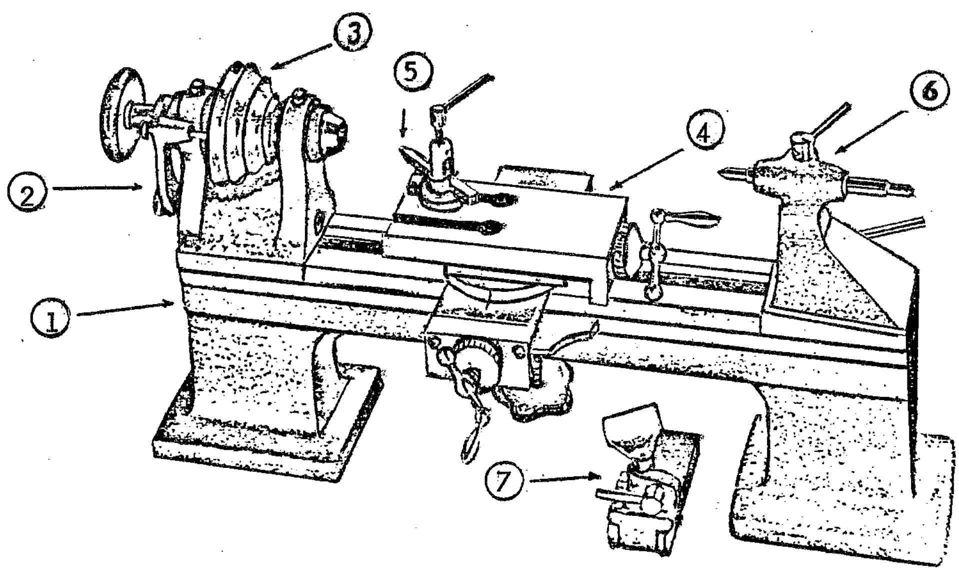
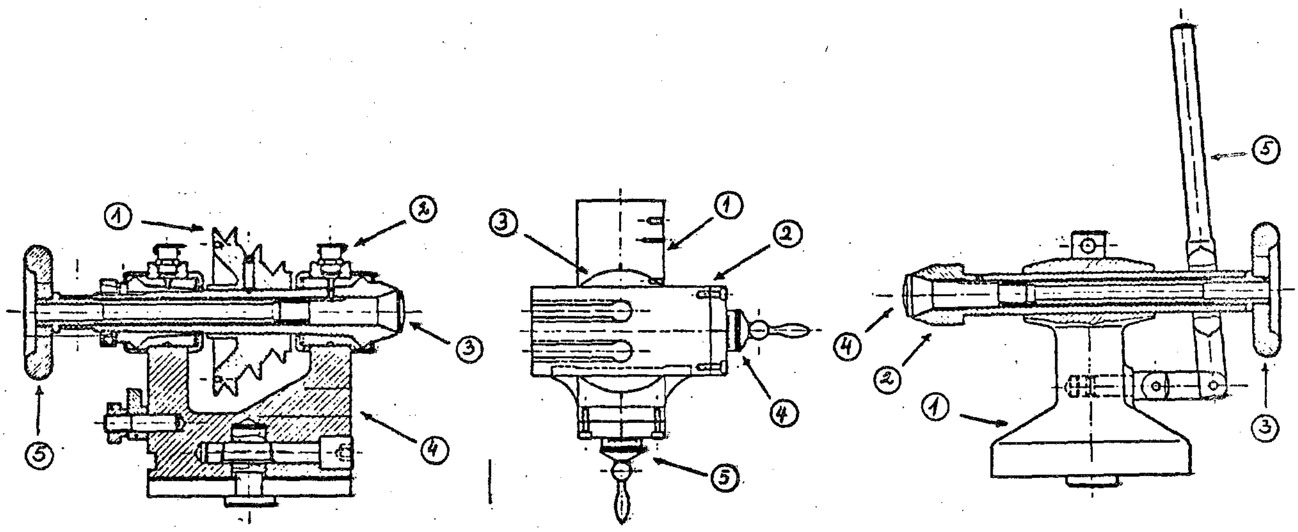


Figure 171 - Watchmaker's turning lathe

The turning lathe consists of a cast-iron bed (1), carrying the head-stock (2), with the spindle rotated by an electric motor (not shown in the figure) through a belt-drive and the three-step pulley (3). A hand-operated compound slide rest (4), carrying the cutting-tool (5), is fixed to the bed by a fast-release screw-lock. At the other end of the bed rests the tail-stock (6) with the male and female centres. Instead of the compound slide rest (4), a so-called T-rest (7) can be locked in its place, permitting manual operation of the cutting-tool. The T-rest usually has interchangeable top cutting-tool supports, differing in width from the tool supporting edge.

Cut-away views of the head-stock, compound slide rest and an alternative to the tail-stock, the drilling tail-stock, are shown in Figure 172 (a), (b) and (c) respectively.



(a) (b) (c)

Figure 172 - Turning lathe head-stock, compound slide rest and tail-stock

The spindle, which accommodates the exchangeable split-chucks (3) (Figure 173), turns in two brass bush bearings, oiled through two lubrication caps (front lubrication cap (2) is indicated). The split-chucks with a shank diameter of 8 mm are held in place in the hollow spindle by a hollow screw, which takes the threaded shank. The outer end of the screw is provided with a wheel-shaped handle for screwing and un-screwing the split-chucks for their exchange, or for removing and inserting the piece being processed. A set of split-chucks having different bores, from 0.1 mm to 7.2 mm (indicated on their face), are kept in a box.

The rotational speed of the spindle is controlled in steps through the belt-drive pulley combination and continuously through a foot-rheostat, which controls the current through the motor.

The compound slide rest, Figure 172 (b), with the transverse (2) and top (1) slides, is controlled through two micrometer screws provided with handles and verniers (4) and (5), graduated in parts of 0.02 mm. The top slide, with its locking screw loosened, can be swivelled through 180° on a graduated scale, thus making possible the cutting of the processed surface in the shape of a cone. The compound slide rest carries a cutting-tool post, having a lever-actuated clamping screw.

In addition to the ordinary tail-stock, enabling the processing of long cylindrical objects by centring their free end through the support action of the male or female centre, there is a drilling tail-stock (Figure 172 (c)). The drill-bits used are clamped firmly with the help of the corresponding split-chuck bedded into the adjustable drilling runner (2). The split-chuck is held in place by a long hollow screw with a wheel-shaped handle (3). The drilling runner is actuated by a lever (5). The base of the tail-stock is usually made of cast-iron. It is provided with a fast-action locking screw, which makes fixing of the tail-stock possible at any desired place along the turning-lathe's bed.

Various types of split-, three- and six-chuck collets are shown in Figure 173.

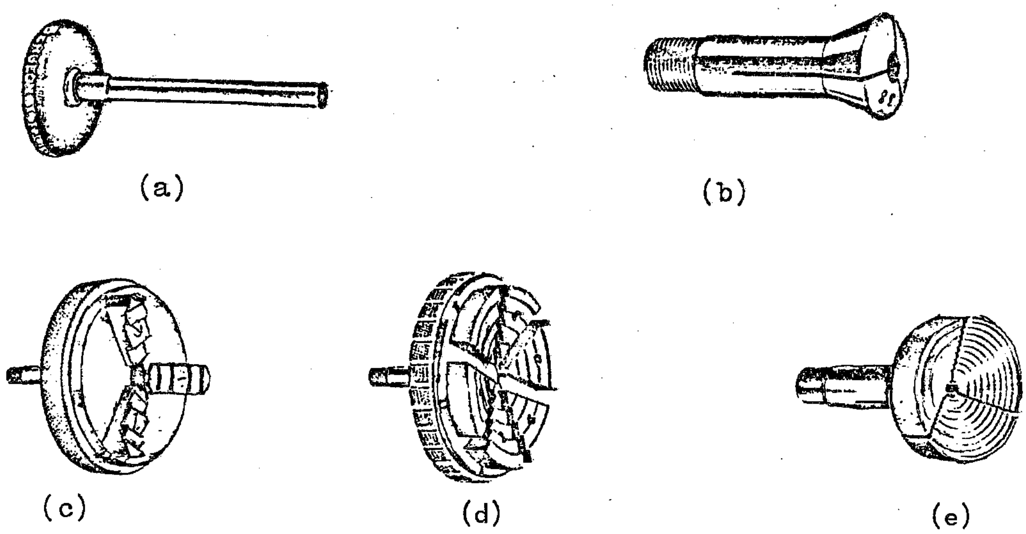


Figure 173 - Turning-lathe collets: (a) split-chuck collet clamping screw; (b) ordinary split-chuck collet; (c) universal three-chuck; (d) universal six-chuck; (e) disk split-chucks collet

Modern watchmaker's turning lathes are provided with a number of attachments enabling thread-cutting, drilling and milling operations. Almost any clock component can be made using such combinations.

A machine-tool which has lesser application to watch-repairs but is of importance in fine mechanics is the engraving machine (Figure 174). The one presented in the figure is the simplest version, capable of engraving letters, numbers and linear scales. More complicated engraving machines, provided with rotary feed-table and accessories, can be used for engraving circular scales as well.

The main parts of the machine presented in Figure 174 are as follows: (1) base plate; (2) pattern holder on slide rail; (3) electric motor; (4) parallelogram frame; (5) vertical-travel column; (6) vertical-travel micrometer screw; (7) vertical-travel locking screw; (8) top-slide; (9) universal vice; (10) micrometer screw - longitudinal slide; (11) following finger; (12) pattern stop. (A milling cutter holder is not illustrated.)

Engraving machines having their parallelogram frame-beams of an adjustable length are capable of a change in scale of the pattern replica, as well as of a change in the inclination in respect to the vertical of the engraved symbols.

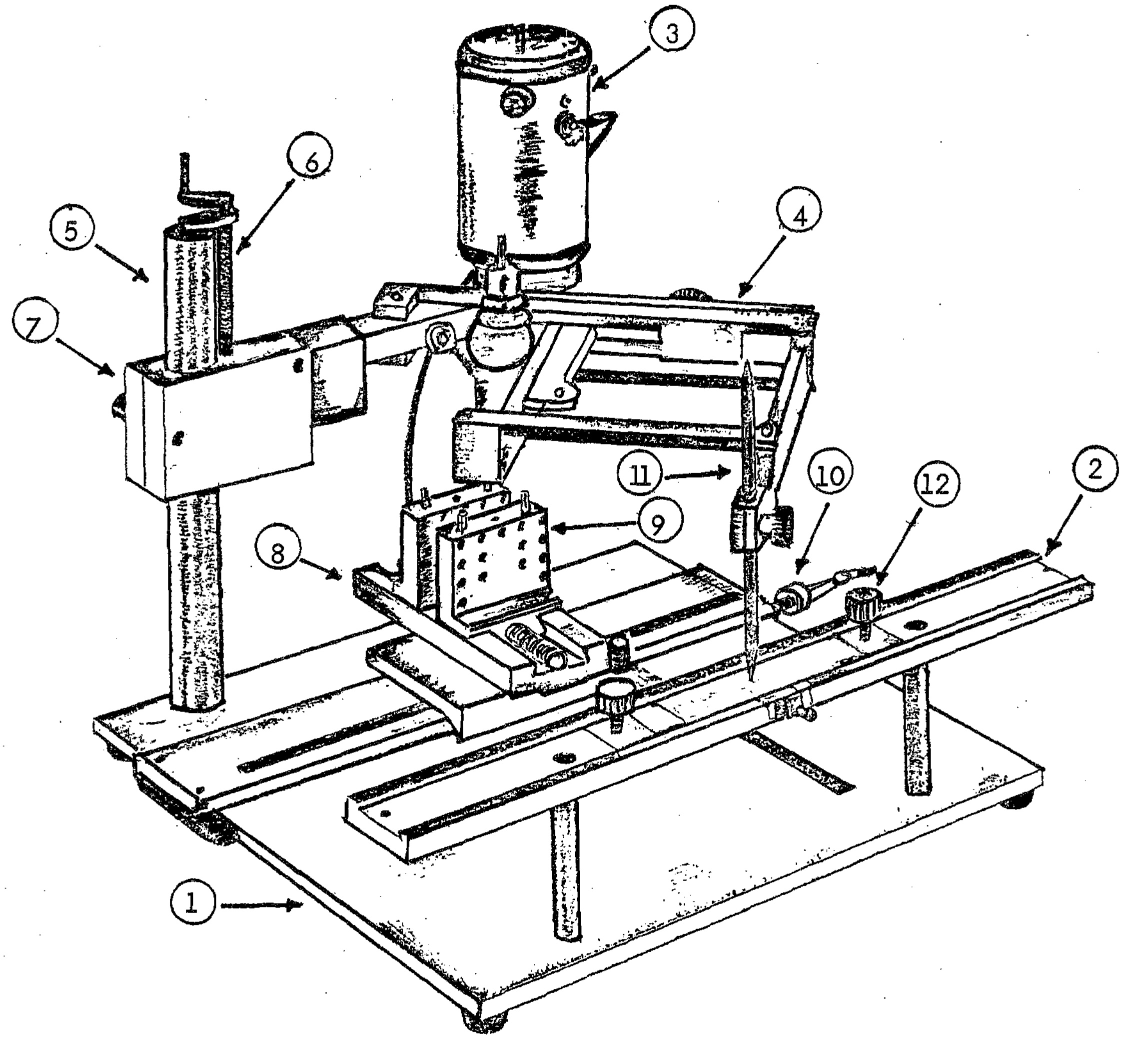


Figure 174 - Engraving machine

The object to be engraved is held between the jaws of the vice in a perfectly horizontal position (otherwise the depth of the cut will vary). Circular objects are held between the four protruding posts on the vice. Using the cross- and longitudinal-travel micrometer screws, the spot on the object where the cutting should start is brought beneath the cutting tool. Care should be taken that the "following finger" stays at the beginning of the pattern to be followed, while working with the micrometer screws. With the motor running, the milling cutter is lowered using the micrometer screw until the desired depth of cut is obtained. The following finger is made slowly to track the engraved symbol. For the next symbol, the engraving tool is lifted and lowered again at the desired spot. If the cut obtained is too shallow, the operation may be repeated.

Among the accessories for the engraving machine, there are various cutters, sets of pattern symbols (letters, numbers) and wrenches, a tool-grinder, etc.

A great variety of special watchmaker's tools are available commercially. The basic tools listed in the following pages are those used in routine fine-mechanics work.

A staking tool (Figure 175) is used for removing rivets and punching holes in springs for the purpose of riveting. It consists of a cast-iron pedestral with a C-shaped punch-holder. The punch used is centred exactly above a hole of the desired diameter on a swivel riveting disk. The action of the device resembles somewhat that of a small press, except that the punch is driven into the material by the force of the hammer.

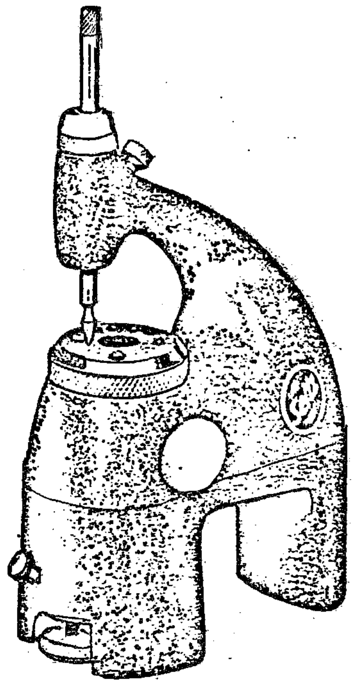


Figure 175 - Staking tool

A set of punches with tips of different sizes and shapes accompanies the staking tool. The punches, as well as the swivel disk are made of extra-hardened steel, capable of withstanding the wear at the cutting edges, caused especially by the punching of the tempered ends of the main springs.

A set of three pin-vices is shown in Figure 176, each with a different collet opening (0 - 0.8 mm, 0 - 1 mm, 0 - 1.2 mm). Pin-vices, as the name of the instrument implies, are used in holding small circular objects, while grinding or filing them. A complete set of pin-vices, their respective bores ranging from a fraction of a millimetre up to 3 mm are widely used in fine mechanics.

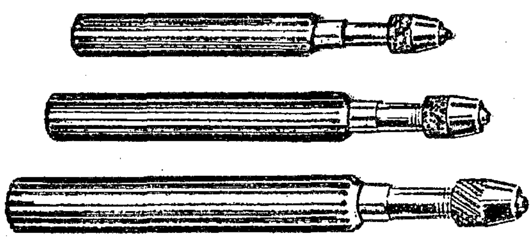


Figure 176 - Pin-vices

Different versions of riveting stakes are shown in Figure 177. Like the staking tool already described, they are used with a set of punches for removing rivets.

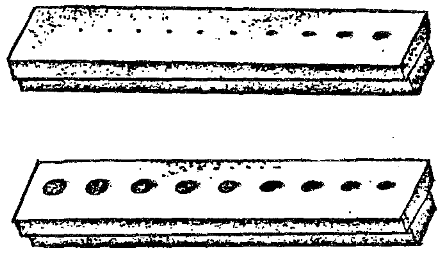


Figure 177 - Riveting stakes

An assortment of ten shaped cutters is shown in Figure 178. Shaped cutters are used together with a flexible-hose drive and cutter holder - an attachment to the ordinary table-top drilling machine. Shaped cutters, irrespective of their cutting-head size, have a 3-mm diameter shank.

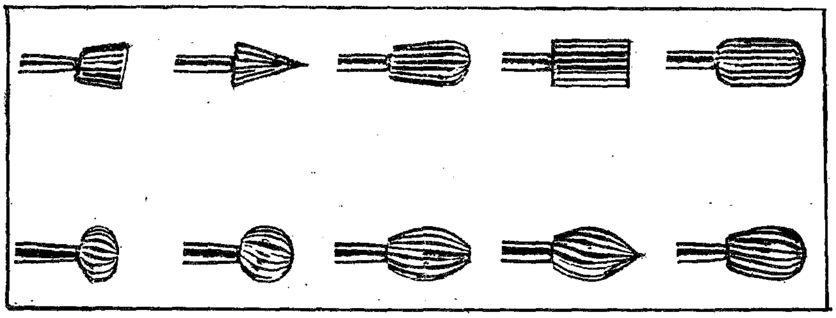


Figure 178 - Shaped cutters - 3-mm shank

Figure 179 illustrates various types of hammer. Hammers are classified according to their weight; those used in fine mechanics range in weight from 40 to 300 g.

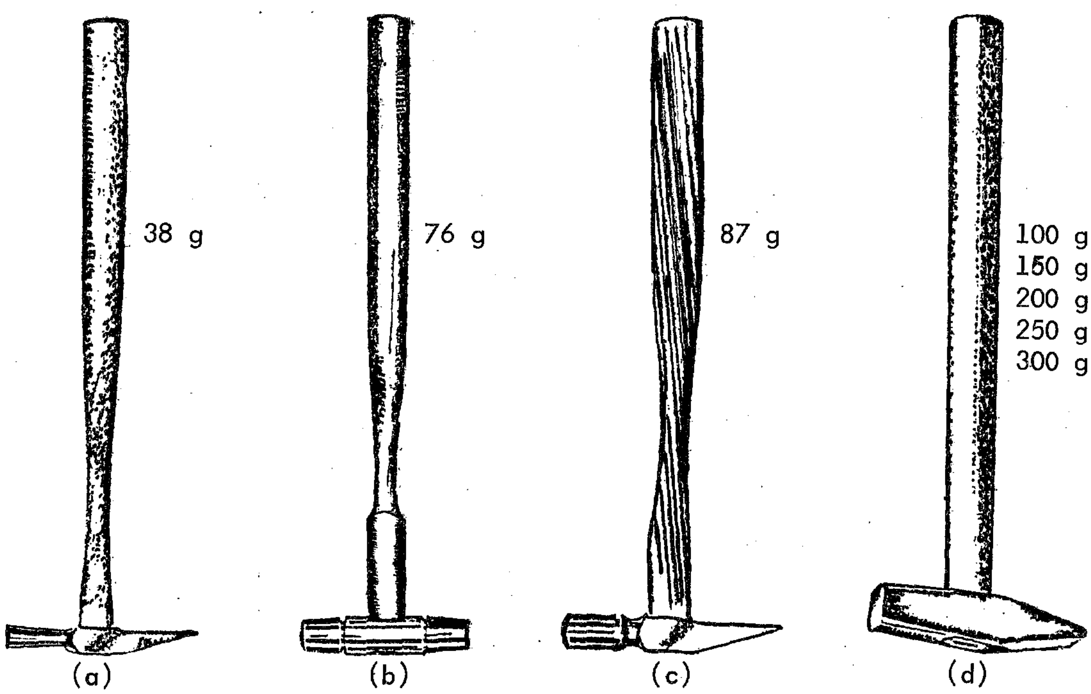


Figure 179 - Set of hammers: (a) ordinary steel watchmater's hammer; (b) brass hammer; (c) insulated hammer; (d) mechanic's hammer

Pliers are indispensable hand-tools for the fine mechanic. A set of watchmaker's pliers are shown in Figure 180: flat-nosed, round, half-round, straight-end cutting, oblique-end cutting and side-cutting. Ordinary combination pliers are not shown.

A set of watchmaker's tweezers are shown in Figure 181. From top to bottom: flat steel tweezers, steel point, nickel-steel tweezers, steel-fibre points (for oiling of the mainspring), jeweller's steel type, nickel steel with cutting jaws, nickel steel for hand removing, nickel-steel collet remover, steel with shovel, iron wire with flat jaws, steel tweezers for holding balance jewels and cap- jewels of shock-absorbers.

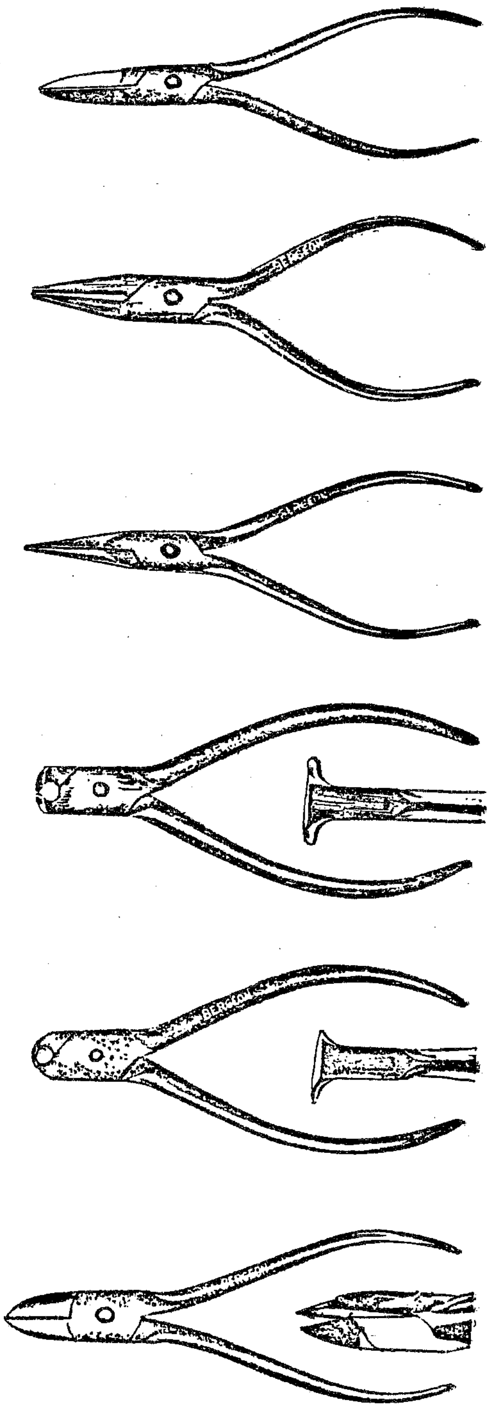


Figure 180 - Pliers

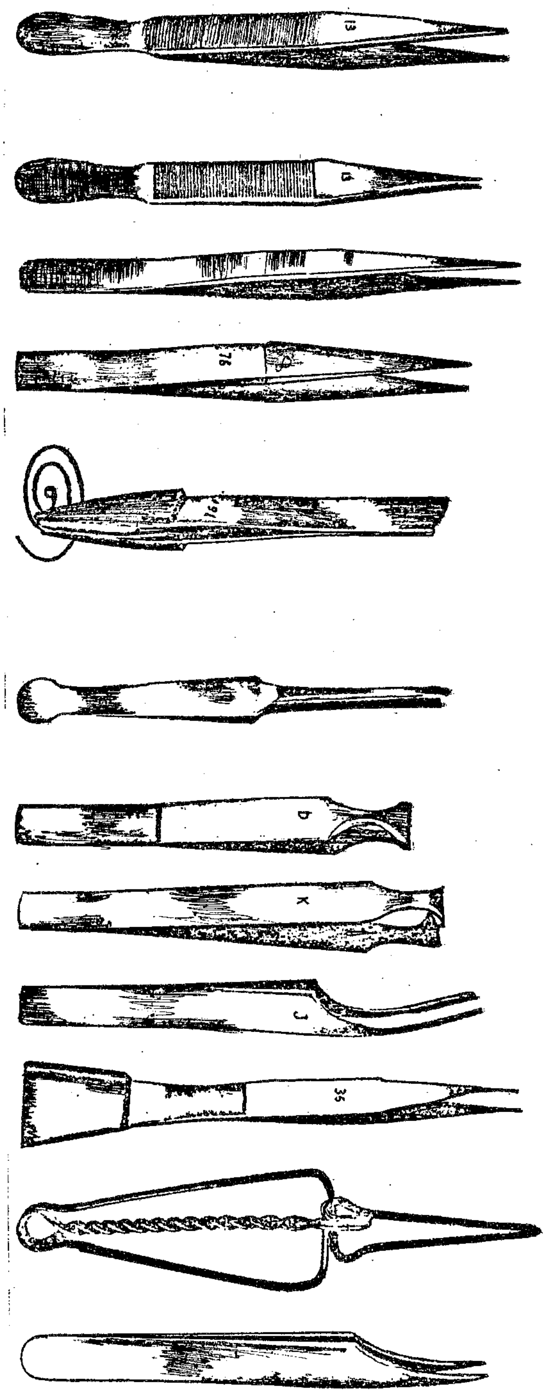


Figure 181 - Tweezers

The list of watchmaker's hand-tools could be continued with a set of screwdrivers, files, (second-cut, smooth and dead smooth (flat, round, half-round, square, three-square)), taps and dies for thread-cutting (1, 1.5, 2, 2.6, 3 mm) together with tap-wrench and die-stock, set of drills (from 0.5 to 10 mm), conical stepped-increase diameter cutting-tool for hole enlarging, counter-sink cutting-tools, miniature screwdriver-handle socket wrenches, set of scissors, knurling rollers, ordinary and watchmaker's locksaw, clockwork cleaning and oiling equipment, etc., etc.

The FMMW may be equipped with special task tools besides the basic, conventional ones, but is is recommended that extra equipment should only be obtained if so warranted by operational requirements.

16.10 Electrical and electronics maintenance workshop (EEMW)

The majority of network meteorological measuring instruments are mechanical. Electrical instruments for measuring meteorological variables started to be used on a regular basis with their mechanical counterparts just after World War II. At the beginning, these included electrical anemometers and anemographs, the classical rotational sensors coupled to electrical signal converters and indicators (recorders). Later, electrical psychrometer aspirator fans appeared, followed by temperature- and humidity-measuring instruments based on electrical principles. As far as the conventional meteorological network station is concerned, the process of "electrification" has been relatively slow, mainly because of the existence of international standards for the unification of meteorological instruments' parameters.

With the expansion of the Meteorological Services and the need to remote more meteorological parameters, further electrical instruments for observing meteorological variables have come into operational use.

The jet-aviation weather-information requirements gave another impetus to the development of electrical and electronic instruments. Research in the atmospheric sciences increased in scope and depth and, as a result, some conventional meteorological instruments were modernized and a number of completely new ones designed, some of them rather sophisticated.

Last but not least, automation trends in data acquisition, processing and storage have caused a steady flow of electronic techniques into the field of meteorology.

At present, based on their specific meteorological applications, the electrical and electronic instruments could be grouped in the following way:

(a) Electrical remote-reading (recording) meteorological instruments (anemometers, radiation-measuring instruments, humidity- and temperature-measuring instruments);

(b) Field-station and airport electronic meteorological instruments (wind, temperature, humidity, cloud ceiling, visibility, etc.);

(c) Upper-air electronic instruments and equipment (radiosounding equipment, weather radars, lidars, acoustic radars, etc.);

(d) Automatic weather stations;

(e) Unique, special-purpose meteorological instruments.

Contemporary techniques of data-processing and telecommunication equipment have been purposely omitted because, despite their widespread use by Meteorological Services, they do not come under the heading of meteorological instrumentation.

The groups of instruments and equipment for meteorological measurements listed above may be divided into two major technological divisions: analogue techniques and digital techniques. Although electronics disciplines, these two divisions differ as far as personnel qualification requirements are concerned.

The objective of the EEMW is to maintain in an operational state the electrical and electronic instruments and equipment used for data acquisition in meteorology. This includes the maintenance and repair of these instruments, as well as testing and adjustment of their electrical and meteorological parameters.

A number of approaches are possible, as far as the EEMW is concerned, in order to fulfill these objectives successfully. The alternative solutions depend, among other things, upon the scope of the projected activities and the diversity of the equipment. Without going into unnecessary detail, it seems that the alternative for a central EEMW, capable of handling equipment listed under (a), (b) and (c) comes closest to the idea of the average EEMW. It should be noted, however, that it is only the analogue-output instruments and equipment which are considered to be subject to the activities of the average EEMW. In addition, major dismantling and repair of equipment like radar, needing special facilities, should be left out of the scope of the average EEMW.

16.10.1 Furniture layout of the average EEMW

EEMWs may vary appreciably in area, depending on work load. An area of 40 m^2 (indicated in section 16.5 as being usually sufficient) will be assumed in the following discussion.

The basic items of furniture for the EEMW are indicated in Figure 182 and a layout is suggested in accordance with section 16.5.

All working benches are similar in size and design. They may be wooden, having two side compartments with drawers to accommodate the electrical and electronic components and hand-tools. It is convenient to have a shelf running from one end of the bench to the other, about 40 cm above the bench-top, for the most frequently-used instruments, which would otherwise clutter the bench-top. The bench-top should be protected from wear by the use of exchangeable plastic overlays.

The cabinets used to accommodate most of the electronic measuring instruments which are not in everyday use can be standard large, metallic, two-storey, and shelved versions of office cabinets with windows in the upper half. In selecting the cabinets, it should be borne in mind that some of the instruments to be kept in them will be rather heavy and bulky.

The philosophy behind the arrangement presented in Figure 182 is explained through the operational flow diagram, shown in Figure 183.

The incoming instruments are cleaned and disassembled at station (1) ready for repair. Electrical instruments, such as remoting anemographs, remote-recording pluviographs, etc., are sent for further maintenance or repair to station (4). Complete overhaul, including oiling and adjustment, mechanical linkages, as well as the necessary repair work on the electrical circuitry, is made at the station (4). Ready for either calibration or shipment back to the field, the instrument is returned to station (1) for further action.

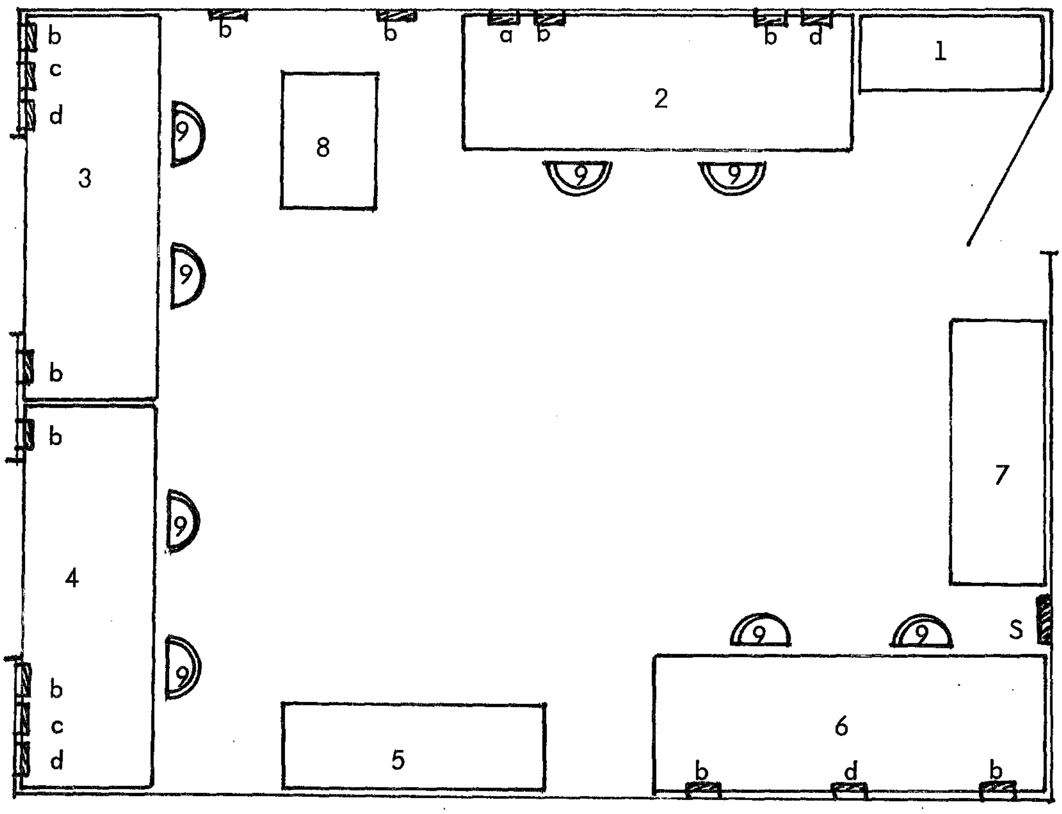


Figure 182 - Example of an EEMW furniture layout: (a) power outlet, three-phase 380 V/3 kW; (b) power outlet, monophase 220 V/2 kW; (c) power outlet, 250 V d.c.; (d) power outlet, 2 x 12 V d.c.; (S) central workshop power switch; (1) staff overalls/clothing cabinet; (2) working bench of the disassembly/assembly station; (3) electronic measurements and testing station; (4) electronic equipment repair (soldering, wiring) station; (5) electronic measuring instrument cabinet; (6) electrical repair station; (7) electrical and electronic measuring instruments; (8) oscilloscope trolley; (9) swivel chairs

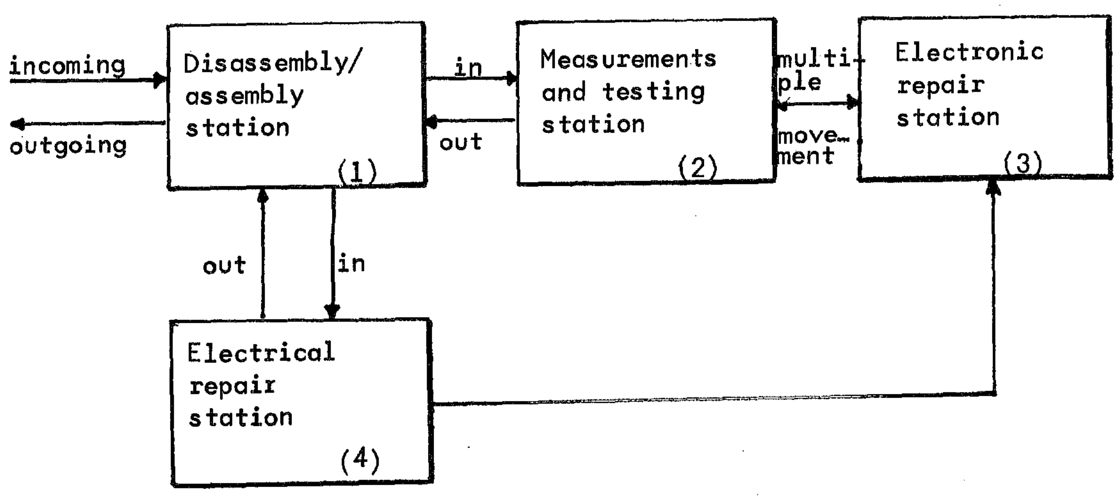


Figure 183 - Flow diagram of EEMW activities

Electrical motors, generators, selsyns, parts of more complex meteorological equipment or electronic equipment, etc., are also sent for repair to station (4) which handles all cases connected with power sources, low- and high-voltage rectifiers, power transformers, etc. The latter, parts of more complicated electronic equipment, are sent from (4) to station (3), which handles the electronic part. The incoming electronic instruments from field stations and airports are directed to stations (2) and (3) for maintenance and repair.

It is the duty of the EEMW to test the electrical and electronic parameters of the repaired equipment. Whenever more specific meteorological tests or calibration of the instrument are necessary, the EEMW should refer to the calibration laboratories. In all such cases, the contact should be maintained on a professional level, between the professionals of the two units concerned, in order that testing and calibration are carried out according to the accepted standards.

16.10.2 EEMW equipment

Generally, the EEMW's equipment will depend on the scope of activities of the workshop. The type and number of measuring instruments and equipment will be linked directly to the workshop's objectives. Approached from this point of view, it seems suitable to discuss the EEMW equipment in terms of three groups:

(a) Technicians' individual tools and instruments;

(b) Universal instruments (equipment);

(c) Special-purpose instruments (equipment).

Whilst equipment for measuring voltage, current, resistance, inductance and capitance has a more universal application than, say, sources of particularly shaped voltage pulses, it has been grouped in this way solely with the aim of providing its most efficient deployment in the workshop area.

The individual tools and instruments are those used and generally looked after personally by technicians in their routine work (often extensively and sometimes exclusively (one tool/instrument set per person)) and on field trips.

With a considerable margin for personal choice, it seems that the list of individual tools and instruments should contain the following items:

(a) Set of hand-tools:

- Set of standard screwdrivers, 3 mm, 4 mm and 6 mm edge;
- Set of Phillips (cross-shaped edge) screwdrivers, 3, 4 and 6 mm;
- Straight tweezers, dentist's concave mirror;
- Set of pliers, diagonal-cutting and long-nosed; wire-strippers;
- Magnifying glass;
- Set of bread-board interconnecting cables, together with banana plugs and crocodile clips;
- Soldering iron, 12 V/12 W, soldering gun (instant) 220 V/120 W flux, solder, pack of fine-grain abrasive paper;
- Set of plastic socket-wrenches and screwdrivers for adjustment of inductance cores;

(b) Set of electrical measuring instruments:

- Neon-bulb voltage indicator;
- Multimeter, 20 000 Ω/V or better, having ranges of (a.c./d.c.): 1, 5, 25, 100, 250, 1 000 V; 0.0001, 0.01, 0.1, 1 and 10 A; Ω, kΩ, or similar;
- Portable Wheatstone bridge, 0.01Ω to 50 kΩ, or similar;
- Portable transistor and diode tester;

(c) Bread-board experimenting stock of components and materials:

- Tin-plated, PVC-insulated, 0.8 mm diameter wiring cable, preferably two rolls of different colour;
- Resistors: 0.25, 0.5, 1 and 2 W power rating, suitable selection ranging from one ohm to one mega-ohm;
- Capacitors, styroflex (or similar), suitable collection in the nanofarad, microfarad range, ceramic: picofarad, tens and hundreds picofarad range and electrolytic capacitors of low (up to 25 V) and high (up to 450 V) voltage rating in the tens, hundreds and thousands microfarad range.

The workshop instruments and equipment of more universal usage can conveniently be located on the working-bench shelf, ready for immediate use. These should include:

(a) Tube (transistor) voltmeter or ohm-meter having an input resistance of 10^6Ω/V or better and suitable measuring ranges, provided possibly with overload protection. Digital read-out instruments are easier to use, but if the workshop's technical level cannot meet the repairs required of digital circuitry, an analogue-display instrument should be chosen for the sake of self-sufficiency;

(b) Table-top resistance, inductance, capacitance bridge;

(c) Radio-frequency millivoltmeter (tube or solid-state) with probing head, total range from a few millivolts to about 10 V suitably divided into several sub-ranges. Radio-frequency range selected according to need (telemetering frequencies allotted to meteorology: around 400 MHz and 1 680 MHz; shortwave is some places as well);

(d) Pico-ammeter, d.c. 1 pA to a few milliamps in several ranges;

(e) Transistor characteriograph, for measuring the parameters of low- and medium-power rating transistors;

(f) Constant-voltage source, voltage value selectable:

(i) Low voltage, 0 - 25 V/2.5 A, or similar;

(ii) High voltage, 0 - 250 V/100 mA, or similar;

(g) Absorption wave-meter, LW, MW, SW possibly UHF RF ranges or higher;

(h) CRT oscilloscope, average ratings (0 - 10 MHz, sensitivity 50 mV/scale division or similar;

(i) Radio-frequency (RF) signal generator, LW, MW, SW possibly UHF, 10 μV-IV to 1 V RF output, or similar;

(j) Audio-frequency (AF) sine-wave signal generator, 20 Hz to 20 kHz - 5 W/5Ω , 600Ω or similar;

The universal electronic instruments listed above may be used in experimental work in addition to routine maintenance. As already mentioned, frequency ranges of equipment should be selected according to the actual need.

The specific-purpose electronic measuring instruments are instruments used in the servicing of a narrower class of electronic meteorological equipment, such as high-frequency-band radiotheodolites, WF radar, lidar ceilographs, etc. A general list of such equipment could contain:

(a) High-frequency signal generator(s) (250 MHz - 2 500 MHz or higher), AM/FM pulse modulation, 0.5 μV - 0.5 V RF output, high frequency stability;

(b) Pulse generator of pulses of either polarity, with pulse-amplitude control of positive and negative pulses and pulse repetition rate controllable within the range 10 Hz - 10 MHz, maximum amplitude 10 V to 50Ω ;

(c) Frequency-meter, analogue read-out 10 Hz - 100 kHz in ranges, minimum input signal 100 mV;

(d) Frequency-meter, digital read-out, 0 - 120 MHz, variable sampling interval, high constancy, timer-generator, minimum signal input 100 mV;

(e) Twin-ray CRT oscilloscope, high-frequency response, high sensitivity;

(f) Set of lumped and distributed-parameter (cavity-resonator absorption wave-meters, covering the frequency range 100 MHz - 2 500 MHz;

(g) High-frequency thermistor power-meter;

(h) High-frequency transmission-line measuring bridge.

The instruments and tools used in the assembly/dissambly station (1) and the repair station (4) may also be considered as belonging to the special-use category, including:

(a) Complete set of mechanical hand-tools for mechanical work (screwdrivers, wrenches, files, pliers, hammers, etc.);

(b) Two bench vices Nos. 3 and 5, installed at either end of the working bench;

(c) Small (450 W) bench-top drill, with a set of drills (1 mm - 10 mm) and machine-vice;

(d) Bench-top grinder (450 W)

(e) Soldering irons, 250 W and 500 W, solder and flux;

(f) Built-in, a.c. volt-ammeter (220 V, 15 A) connected to one of the monophase power outlets;

(g) Variable-speed, electric-motor driven, rotation-motion simulator (for testing rotational wind-signal converters);

(h) Standard resistance-decade box, 0.1 Ω - 10 kΩ ;

(i) A.c./d.c. rectifiers for the EEMW power outlets (not stabilized):

  (i) 2 x 12 V/10 A;

  (ii) 250 V/0.5 A.

The equipment parameters mentioned above should be considered as suggestions and subject to change according to actual needs.

16.10.3 EEMW personnel - qualifications

With the EEMW example discussed, a crew of six - two professionals and four technicians - is considered a suitable complement.

As seen in the table in section 16.8, the technicians - one electrical technician and three electronics technicians - are assumed to be technical-school graduates with on-the-job training. The professionals, having a degree either in engineering or physics, would also benefit very much from preliminary in-service training.

In-service training of technical personnel should include familiarization with new equipment, either in the field under the guidance of an expert, or in training classes, usually carried out by the manufacturer of the equipment, preferably at their own training site.

Both technicians and professionals should be oriented, as far as their qualifications are concerned, in two major fields of the EEMW's activity, e.g. conventional electronic telemetering techniques and microwave and pulse techniques, so as to create two groups of technical personnel whose qualifications complement each other. With an increase in personnel of an EEMW to cover automation, newly-appointed members should also be specialists in the field of digital electronics and automation.

16.11 The mechanical maintenance workshop (MMW)

The MMW takes care of the mechanical maintenance and repairs of meteorological-station instruments and equipment and facilities. Besides the design of simple meteorological instruments and accessories, the MMW has the permanent objective of developing its own technical potential through the design of special machinery, thereby increasing the range of its activities and capacities.

The diversity of the activities of the MMW calls for the establishment of the following sub-units:

(a) Lathe-turning, milling and shaping sub-unit;

(b) Sheet-iron sub-unit;

(c) Forging, gas- and arc-welding sub-unit;

(d) Electroplating sub-unit;

(e) Carpentry sub-unit.

These sub-units complement each other in their activities to attain a completely self-sufficient, compound MMW.

16.11.1 Layout of furniture and machine-tools in the lathe-turning, milling and shaping sub-unit

The basic tools of this workshop are shown in Figures 184, 185 and 186.

The turning-lathe (Figure 184) is used in cutting cylindrical surfaces. The object to be processed is fastened to the face-plate (4) through the four "dogs" (a three- or four-chuck collet is used instead of the face-plate with smaller symmetrical objects). With the object turning, the cutting is done by a cutting tool clamped to the tool box (5). The cutting feed is controlled manually through micrometer screws actuated by handles and provided with large-scale rings for reading the transverse (perpendicular to turning object) and longtitudinal feed motion of the slides (6). With long objects, such as pipes, a universal collet is used to clamp one end, the other being supported by the centre of the tail-stock (8). To prevent the long object being bent by the centrifugal forces of the rotation, an additional support is provided by a stationary steady (7). A moving steady is used with relatively thin objects, which may yield to the transverse feed force (7). For thread-cutting, the saddle bearing the transverse and top slide is moved automatically through the rotation of the longitudinal lead screw (9). Automatic feed, both transverse and longitudinal, is obtained through the feed shaft (10). The chips obtained from the cutting are collected in the chip-tray (12). The gear-box (3), through its control handles, provides for the selection of a suitable turning speed of the spindle, as well as starting the shafts which transmit the motion necessary for the feed in the automatic mode of the machine. A reversal of the turning direction is possible either through the gear-box mechanism or, in simpler machines, by reversing the drive motor.

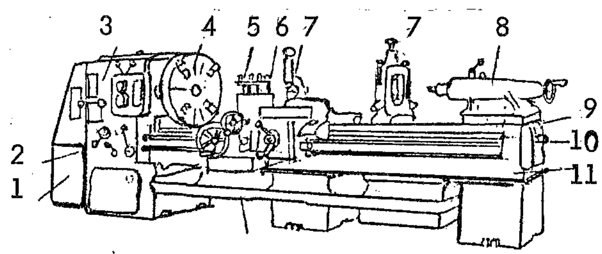


Figure 184 - Turning-lathe (large)

A medium-size turning lathe is shown in Figure 185:

- The distance between the centres of the collet and tail-stock is 1 000 mm;
- The centre height above bed is 190 mm;
- The spindle bore is 44 mm;

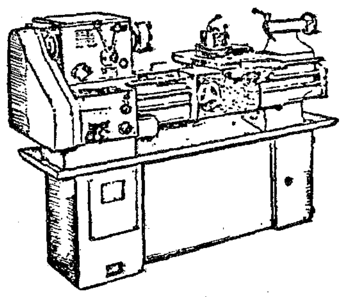


Figure 185 - Medium-size lathe

- The gear-box provides 8 spindle speeds, ranging from 34 r.p.m. to 1 000 r.p.m.;
- The number of feeds is 33, longitudinal feeds ranging from 0.19 to 2.87 millimetres per revolution; transverse feeds 0.09 to 1.31 millimetres per revolution; inch, as well as millimetre thread-cutting is possible with an inch-thread pitch ranging from 3 to 44 threads per inch and a millimetre-thread pitch ranging from 0.25 to 10.5 threads per millimetre, according to accepted thread standards;
- The driving motor has a power rating of 3 kW;
- The net weight of the machine is about 1 000 kg.

The accessories needed for normal operation of the machine are usually kept to hand in a cabinet. A typical list of accessories is as follows: cooling-water liquid coil, face-plate, set of collets (straight and inverse chucks), revolving centres, set of cutting tools, thickness gauge, thread gauge, machine task-light, etc.

A number of hand-tools are used by lathe operators, such as: spanners, thread-cutting tops and dies, reamers, drill bits, files, etc.

The milling machine of contemporary design is a universal machine for cutting the surface of metal plates and making grooves of various profiles, as well as cutting complex shapes in metal and plastic, such as cog-wheels, and other mechanical components. The cutting tool is a rotary milling cutter.

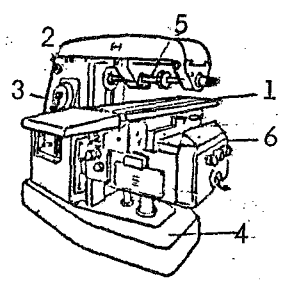


Figure 186 - Milling machine

The classical horizontal milling machine is shown in Figure 186. The object to be processed, which may be of another material, is fastened to the work-table (1) usually by "dogs" (screw-held clamps). With the help of three micrometer screws actuated by handles, the table can be moved left and right (longitudinal), to and from (transverse) and up and down (depth of cut). The driving motor is mounted on the frame (2), containing the gear-box (3) and rests on the pedestal (4). The C-shaped frame carries in its upper part the arbor to which is attached the milling cutter (5). The automatic feed is controlled by the feed-gear (6).

A rotary-feed table presents the possibility of cutting more complicated shapes. It can be attached as an addition to the work table.

An example of an average machine specification follows:

Table size	1 200 x 260 mm
Longitudinal travel	750 mm
Vertical travel	500 mm
Transverse travel	200 mm
Number of feeds	12
Longitudinal feed	26 - 1 200 mm min^{-1}
Transverse feed	26 - 1 200 mm min^{-1}
Vertical feed	13 - 600 mm min^{-1}
Fast-approach travel	3 000 mm min^{-1}
Spindle-speed range	44 - 2 000 r.p.m.
Power rating of motor	4.4 kW
Net weight	1 200 kg

Universal milling machines are a combination of both horizontal and vertical milling machines (the spindle can be turned at right-angles to the longitudinal direction of the table and is adjustable in any desired position).

The shaping machine is used in the processing of plane surfaces by a sliding cutting-tool (Figure 187). The metal object to be processed is fastened to the work-table (1), which can be moved vertically by an actuating handle (2) and transversally by two micrometer screws (3). The depth of cut is controlled by another micrometer screw (4), which controls the tool holder. The frame (5), resting on the pedestal (6), accommodates the gear which transforms the rotary motion of the driving motor (7), into a swinging motion of the sled (8), carrying the cutting-tool (9). The cutting-tool is clamped to a pivoted tool-box. During the forward motion of the sled the cutting-tool cuts, while on its way back it is relieved by the pivot and slides freely along the processed surface of the object. At each backward movement of the sled the transverse control (3), is turned by a fraction, bringing a portion of the surface to be cut under the cutting-tool. This can also be done automatically, by an automatic transverse-transport mechanism coupled to the gear-box.

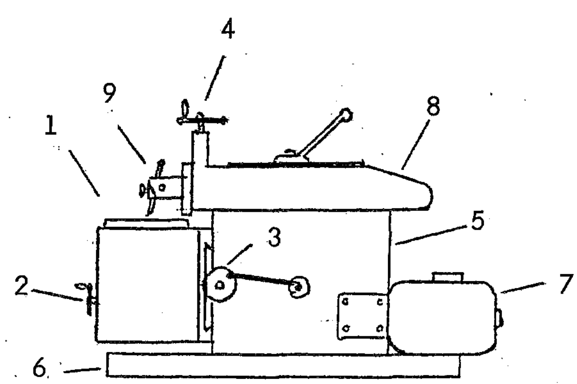


Figure 187 - Shaping machine

Example of specifications (small machine)

Maximum length of cut	350 mm
Transverse travel	400 mm
Vertical travel	350 mm
Range of swinging speed of sled	15 - 200 swing min^{-1}
Range of feed per swing	0.15 - 2.5 mm $swing^{-1}$
Motor power	3 kW
Net weight	1 000 kg

The accessories consist of:

- Set of cutting tools;
- Set of spanners;
- Oiling can;
- Cleaning brush;
- Task-light.

Based on the discussions in section 16.5 and on Figures 184 - 187, the following furniture and equipment layout for the lathe, milling and shaping sub-unit is suggested (Figure 188): turning lathe next to the window; milling machine and shaping machine side by side close to the wall; motor hack-saw outside and close to the hardware storage space. The furniture consists of a standard work-bench and two cabinets: one for the overalls and one for the machine accessories.

This layout is suggested, assuming a heavy machine-tool work-load (in order of priority): turning lathe; milling machine and shaping machine.

Further, it is assumed that the workshop will be run by two workers: one lathe-operator and one milling-machine/shaping-machine operator. Following these assumptions, the best lighting conditions have been chosen for the position of the lathe. The other machines will have to rely chiefly on artificial electric light.

The motor-driven hack-saw, a necessary machine tool for this workshop, has to be installed near the hardware storage place, because manipulation space needs to be large. Moreover, the proximity of the machine to the store will save time and effort in the transport of the materials, which have to be cut from the stock. The work-bench (8) is used in certain fitting operations, which may be necessary for the machining activities, hence the table-top drill and set of fitter's hand-tools. The cabinet (5) provides storage space for the accessories of the three machines. The tool-grinder (2) is of immediate use for sharpening the cutting tools of the lathe and shaping machines. A larger, floor model, next to the tool-storage room, has the same purpose.

16.11.2 Layout of furniture and equipment in the sheet-iron workshop

The sheet-iron sub-unit incorporates the fitter's workshop. The selection of equipment is based primarily on the activities connected with the repair and small-scale production of instruments such as evaporation pans, raingauges, soil-thermometer stands, etc., as well as equipment cabinets, sheet-iron ducts, etc., for the workshops and laboratories. The workshop will deal mainly with low-carbon sheet-iron of thicknesses up to 1.5 mm, aluminium sheets of various thicknesses, and smaller-calibre iron and steel bars.

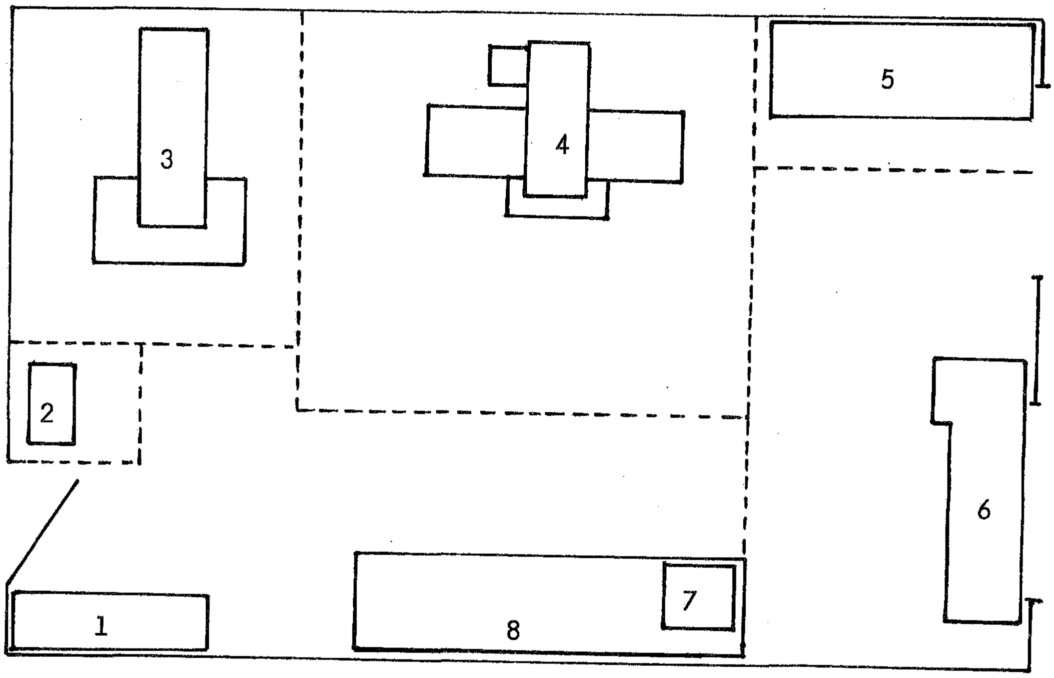


Figure 188 - Workshop equipment layout: 1 - cabinet for overalls; 2 - floor tool-grinder; 3 - shaping machine; 4 - milling machine; 5 - cabinet for accessories and tools; 6 - turning lathe; 7 - bench-top drill; 8 - work bench

The furniture, metallic cabinets and hard-top benches are of the standard design already discussed in previous paragraphs;

An example layout is presented in Figure 189.

Attached to the work-benches are the following tools: mandrel press, lever-arm punch press, hand-operated plate shears, vices, etc. In addition, bench drawers and wall tool-boards contain sets of fitters' and plumbers' tools and instruments.

Hand-operated plate shears (Figure 190) are used in cutting plate and round bar stock of varying thickness and diameter. The operating lever (L) is connected via a magnifying linkage to the upper blade (B). A catch-and-locking device keeps the lever in a raised position and prevents accidents.

Different sizes of hand-operated plate shears have different cutting capacities. One suitable for the average workshop would have a blade length of 160 mm and a maximum thickness of the plate cut of 4 mm (steel). Such an instrument would weigh about 10 kg.

Hand-operated guillotine shears (Figure 191) are used in cutting large sheets of metal along a straight line. They are stand-mounted to provide extra support to the sheet to be cut. The upper moving blade (B) is attached directly to the lever-arm (L). A counter-weight (W) balances the lever in a neutral balance. An adjustable fence (F) facilitates the cutting of the sheet into strips of the desired width.

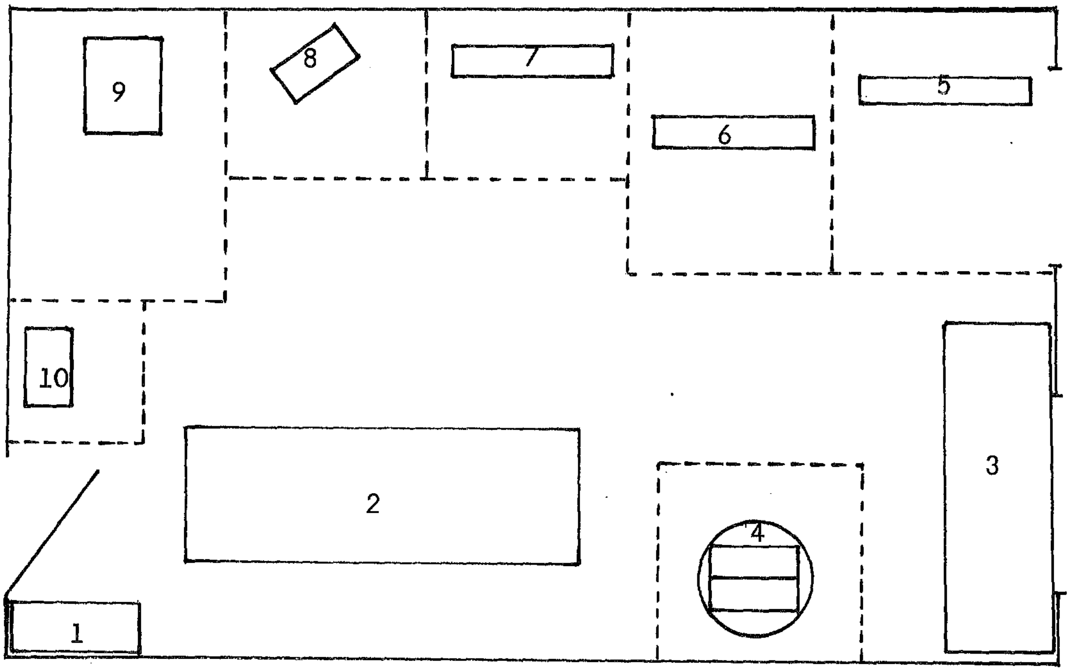


Figure 189 - Sheet-iron workshop : 1 - work-clothes cabinet; 2 - working bench, wide; 3 - work-bench; 4 -fly press; 5 - bending machine; 6 - guillotine shears; 7 - cylinder rolling machine; 8 - flangeing machine; 9 - pillar-drill; 10 - tool grinder

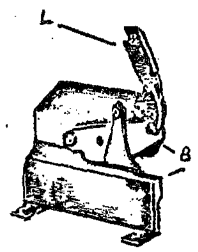


Figure 190 - Plate shears

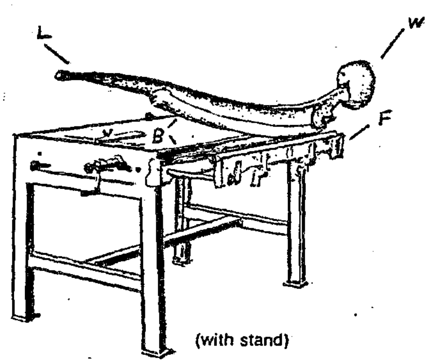


Figure 191 - Guillotine shears

Cutting length	1 020	mm
Maximum thickness of steel sheet	1.5	mm
Table (stand)	1 050 x 720	
Net weight	350	kg

If a metal sheet has to be bent along a straight edge at a desired angle, a bending machine is used (Figure 192). The sheet is held firmly between two metal plates (formers) and the bending force is applied to a third, pivoted one. The machine is hand-operated. An adjustable angle-stop enables the repeated operation of identical bends.

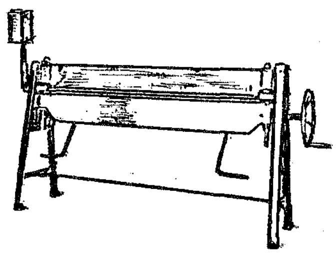


Figure 192 - Bending machine

Working length	1 020	mm
Maximum thickness of sheet	1.5	mm
Net weight (with stand)	300	kg

The circle-cutting machine makes use of rotary cutting rollers to cut a piece of metal sheet to a circular shape of a desired diameter. Cutting a metal sheet along a circular cutting path (or other) is possible with hand-held electrical piston-shears but more attention and skill on the part of the operator are required.

The flanging machine can roller-press the end of a metal sheet or cylinder into the desired flange. The upper roller of the machine is controlled by a screw so that sheets of different thickness can be processed. The flangeing machine is operated by the manual turning of a crank.

With the cylinder-rolling machine, a piece of rectangular metal sheet is passed between three rotating cylinder-rollers, the distance between their shafts being adjustable. Depending on that distance and the elastic properties of the metal sheet, a cylinder is obtained of a desired diameter. The cylinder-forming machine is also operated by the manual turning of a crank.

The fly-press (Figure 193) makes use of the force of inertia of a fly-wheel (FW) to cold-mould or cut sheet-metal. The rotary motion of the fly-wheel is converted into a linear motion of the punch (P) through a sturdy steel spindle with triple-start thread. The punch is guided by slide-guides, securing high accuracy of the pressing operation. The female mould is fastened to the table of the press (T). The cast-iron frame (F) is specially reinforced to prevent distortion.

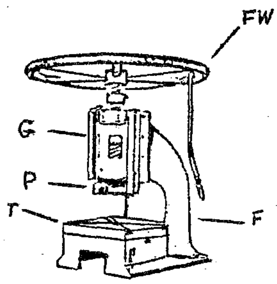


Figure 193 - Fly-press

Example specifications:

Maximum pressure	18.5 tonnes (185 kN)
Threaded spindle diameter	65 mm
Distance: slide centre/frame	180 mm
Maximum stroke	150 mm
Slide-tool holder diameter	32 mm
Base dimensions	400 x 300 mm
Net weight	415 kg

The mandrel press is designed for the press-fitting into and extracting from the workpiece of bushes, shafts, mandrels, bearings, etc. and is useful in machine maintenance. The one pictured in Figure 194 has a cast-iron C-shaped frame and a toothed rack-and-pinion drive.

Operating pressure	1 tonne
Toothed rack diameter	40 mm
Maximum distance between rack and table	225 mm
Distance between centre line of rack and frame	160 mm
Weight	45 kg

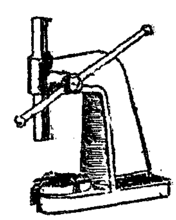


Figure 194 - Mandrel press

The pilar-drill, Figure 195, is a heavy-duty vertical drilling machine, supported by a machine column (pillar) with slide (5), resting on a slotted base-plate (2). The torque of the motor (3), is transmitted to the drill-collet and drill-bit (4), by a step-down revolution speed-controllable gear, which gives the automatic feed as well (gear-box (5)). Manual control of the drilling feed is obtained through the lever (6). A work table (7), slewing and adjustable for height, enables drilling at an angle.

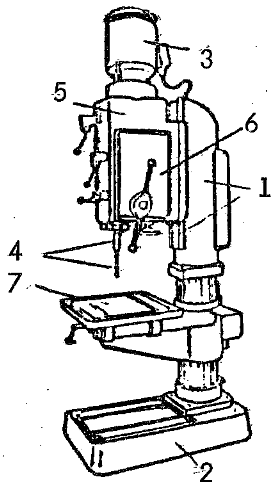


Figure 195 - Pillar-drill

Drill-collets are made for the following maximum diameters of the drill-bit: 6 mm, 12 mm, 18 mm and 25 mm. The power necessary is a function of the drill-bit diameter D:

$$N = 0.02\ D^{1.5}\ (kW)$$

Modern drilling machines are provided with a continuous speed control, usually within 100 - 2 000 r.p.m. The drilling-feed ranges from 0.1 mm to 1.0 mm and the net weight is between 700 kg and 1 500 kg, depending on the model and drilling diameter.

A number of hand-tools are used in the routine work of the sub-unit and others should be added for fitting and plumbing activities, the more important items being:

- Hammers: ordinary mechanics', a set of hundreds of grams and kilogram sizes; rubber mallets (various sizes), drifts (handle-held auxiliary tools);
- Chisels: flat, cross-cut, key-way;
- Punches: round, centre, screw-punches (for cutting large holes);
- Trepanning cutters for cutting soft material washers, (a set);
- Combination stamps for pressing numbers on metal;
- Files: square, three-square, round, half-round, flat (second-cut, smooth and dead-smooth types);

- Wrenches, spanners: open-ended spanners, ring, hexagon-socket, tubular, adjustable;
- Screwdrivers: ordinary and Phillips types, all sizes from 3 mm, hexagon-socket, ratchet with exchangeable blades;
- Sets of dies and taps (thread-cutting): millimetric and inch, together with the tap-wrench and stock, blind-hole thread-cutting taps;
- Pliers: combination, round-nose, gas-pliers, end-cutting, toggle-jointed cutting nippers, lead-pipe expanders;
- Drills: high-speed twist drills with straight shanks, all sizes between 1 mm and 25 mm; deep-hole drills (nose angle 135°, helix 40° extra-wide flutes); aluminium drills; brass drills (point angle 118°, helix 15°, polished flutes); carbide-tip drills (for masonry); pop-rivet drills (for thin sheets); countersink drills; cone-cut crills; graduated drills (for opening holes in thin sheets); portable electrical (250 W) hand-drill;
- Reamers: taper, expanding (with or without micrometer setting of cutting diameter);
- Scissors: book-binding, jewellers' snips, hand-held plate, electrical motor-driven;
- Vices: table (bench), machine, hand-vice;
- Measuring tools: depth-gauge, micrometer, thickness-gauge, gap-gauge, feeler gauge, steel rule, square;
- Soldering tools: soldering iron (500 W), soldering stone, soldering-tin, soldering flux, scraper;
- Plumber's tools: spring-pressure gauge, pipe-burring reamer, hollow milling cutter, gas-pipe cutter, thread-cutting ratchet clamp, plumber's portable tripod, pipe-bending contrivance, gasoline blow-lamp;
- Lifting equipment: folding tripod, pulley blocks, rope, workshop trolley.

16.11.3 Forging, gas- and arc-welding workshop

The technical activities of this sub-unit are arc-, gas- and spot-welding. Maintenance of station facilities is carried out routinely, repairs being performed on various instrument stands, towers, masts, etc. Maintenance and repair of laboratory and workshop facilities are also part of the routine workload. New designs may be called for, usually of simple mechanical instruments and accessories, such as hand-operated soil-samplers, air-tight aluminium containers for soil samples (for gravimetric soil-moisture estimation), Wild (heavy-plate) anemometers, etc.

The workshop has to include in its activities the mechanical cleaning and polishing of articles to be electroplated. The workload in this respect would depend greatly, especially as far as silver-plating is concerned, on the design activities of the electronics workshop.

The forging/welding sub-unit is not supposed to work at full equipment capacity at any one time. As is the case with the other workshops already discussed, the activities connected with different tools and equipment have a sequential rather than a simultaneous character. This makes it possible, depending on the actual workload, to staff the workshops with fewer workers, each one having several technical skills. The working crew is assumed to consist of two: a welder having knowledge of the blacksmith's craft and an assistant. Vocational training for both will be sufficient in most cases.

The layout of the equipment in the workshop is presented in Figure 196. As already indicated in section 16.5 the workshop needs an exit to the outdoor working area, where bulkier elements may be repaired.

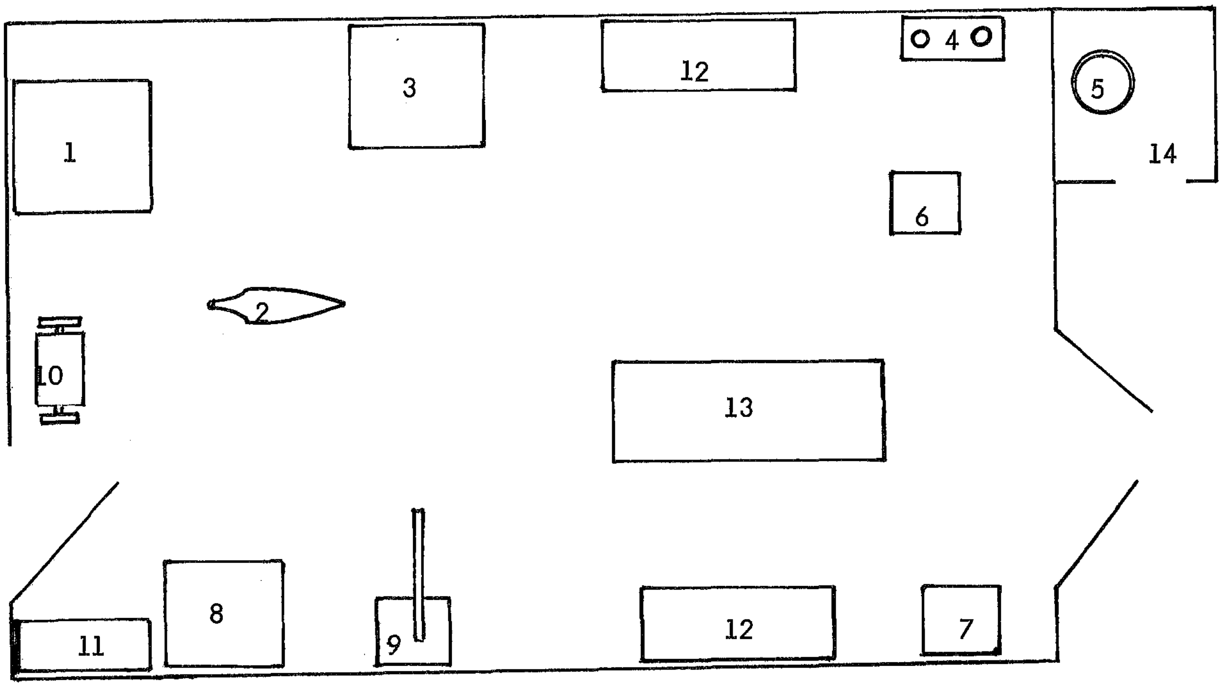


Figure 196 - Layout of equipment in the forging/welding sub-unit

The following major items are indicated in the figure:

(1) portable forge: this is used whenever heat is required to be applied in the shaping of an iron article, e.g. forging, bending of steel clamps, iron pegs and instrument props. The heat is obtained by burning charcoal, which is fanned by a blower. A smoke collector, preferably one using an additional fan, should be installed above the fire-pan;

(2) anvil;

(3) working-bench, iron-plate top, L-shaped steel supporting construction; net weight about 85 kg;

(4) rack for oxygen and acetylene cylinders;

(5) acetylene gas generator;

(6) brick-top, swivel welding table with electrical gas-lighter;

(7) arc-welding transformer, 220 V/50 Hz/33 A(7.5 kW); secondary, 55 V/50 - 180 A, maximum core wire diameter, 5 mm;

(8) hardening oven, t^{o}_{max} = 1 150°C, 220 V/12 kW, 36-litre working capacity;

(9) spot-welding machine, 220 V/50 Hz/3.5 kW; secondary, 1.1 to 3 V; maximum thickness of welded sheets 1.5 + 1.5 mm, stepped-current selector control, maximum electrode pressure: 100 kg;

(10) combined motor-driven wire-brush and mop polishing device*;

(11) work-clothes cabinet;

(12) open-front, shelved cabinets (for welding-equipment accessories);

(13) variable-height welding table, iron-plate top;

(14) gas-generator booth (outdoor).

A list of additional tools and instruments might contain the following items:

- Forging hand-tools and accessories: water trough, hammers (heavy mechanic's, flat, smoothing, cross-hammer, sledge-hammer), hot-chisel, forge tongues, gorge-thickness gauge, etc.;

- Gas-welding kit: eight-piece combined welding and cutting torches, cutter-roller guide, reinforced rubber pressure hose, pressure-reduction valve with pressure gauges (oxygen 200 kg cm^{-2} - 8 kg cm^{-2}; acetylene 25 kg cm^{-2} - 2.5 kg cm^{-2}), welder's goggles and gloves, leather apron. Gas-welding torches can be used in welding and cutting low-carbon steel of thickness 0.5 - 30 mm;

- Arc-welding accessories: cable, electrode clamp and earthing clamp, hand-vices, welder's helmet, gloves, apron, slag-hammer, chisel, angle grinder/cutter. Stock of carbon and coated-wire electrodes (2 mm, 3 mm, 4 mm, 5 mm), portable welding shields, 1.5 m high, for arc-light protection, forced-ventilation smoke-duct.

Special attention should be paid to the forging/welding workshop electrical power installation. Several three- and mono-phase power outlets of high-power rating should be made available at convenient places in the room. An extension line of about 30 mm^2 wire cross-section and 50 m length, together with a cable-drum and trolley and the necessary switching and fuse arrangements would be very useful in outdoor arc-welding activities.

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* Motor-driven polishing devices used in electroplating usually have a 1 500 W power rating and high-revolution speed (mop polishing disk peripheral speeds are about 3 000 m min^{-1}).

16.11.4 Electroplating workshop

The electroplating workshop is an auxiliary MMW unit, whose activities support the maintenance and design activities of the electronics and machine-tool workshops. Two kinds of electroplating activities are considered: nickel-plating of instruments' components, screws and nuts to make them weather-resistant; and silver-plating of electronic instruments' components to improve their electrical parameters or to repair worn-out contacts.

Three main groups of operations are considered, as far as electroplating is concerned:

(a) Mechanical cleaning of articles to be electroplated

- Brush cleaning;
- Smoothing;
- Polishing;

(b) Chemical cleaning

- Base-solution grease cleaning;
- Acid-solution oxide removing;
- Cyanide-solution processing;
- Clean-water washing;

(c) Electroplating, washing and drying

- Nickel-plating in acid electrolytic bath;
- Silver-plating in cyanide electrolytic bath.

The first group of operations, the mechanical cleaning of the articles to be electroplated, will normally be carried out in the forging/welding workshop. The second and third groups of operations will be carried out in the electroplating workshop.

A step-down transformer/rectifier unit will provide one solution to the problem of an electrical current source for the small-scale electroplating workshop. It is a low-voltage (up to 20 V if barrel electroplating is considered), high-current rating (several tens to several hundreds of amperes, depending on the plated area) electrical source, having current-control possibilities (resistance boards) in a wide range.

As traces of impurities in the electrolyte baths are highly detrimental to the quality of the electroplating, it is essential to maintain absolute cleanliness in the workshop. With the limited space of the workshop, this means observing a strict sequence of operations, as well as preventing pollution of the baths by using tight-fitting lids and partitions between the various vats.

The general layout of equipment in the electroplating workshop is suggested by the drawing in Figure 197.

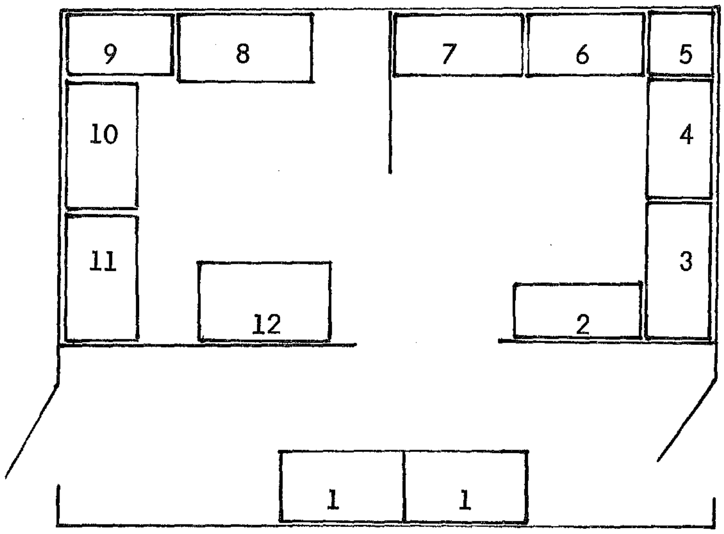


Figure 197 - Example layout of an electroplating workshop

The major items are:

(1) storage cabinets: overalls, goggles, gloves, chemicals and accessories;

(2) base-solution cleaning vat;

(3) running-water cleaning vat;

(4) nitric-acid-solution cleaning vat (brass, non ferrous articles);

(5) running-water tap and sink;

(6) running-water cleaning vat;

(7) sulphuric-acid-solution cleaning vat (iron and steel articles);

(8) cyanide electrolyte electroplating vat (silver);

(9) step-down transformer/rectifier and current-control resistance board;

(10) acid electrolyte electroplating vat (nickel)(separate articles);

(11) acid electrolyte electroplating vat (nickel bulk-article, barrel-plating);

(12) table with plastic overlay.

The accessories consist of:

- Electrolyte temperature-control instruments;
- Electrolyte heaters;
- Electrolyte mixing device;

- Ph-measuring instrument;
- Voltage- and current-measuring instruments;
- Electrolyte filtering device;
- Ventilation duct.

Because of the risk of spillage of corrosive liquids, it is wise to cover the floor and walls of the workshop with non-corrosive materials.

One technician is assumed to work in the electroplating workshop. If the workload proves less than expected, his part-time employment in other workshop units may be a solution. It will be necessary, however, to appoint one permanent staff-member who will be responsible for the electroplating workshop and who will take care of equipment and expendables.

16.11.5 The carpenter's workshop

The maintenance activities of the carpenter's workshop are connected mainly with the upkeep of furniture and station facilities, as well as with producing woodwork instrument accessories on a small scale. An experienced carpenter in the conditions of the averagely-equipped workshop should be able to cope with work at the level of complexity of a Stevenson screen.

An area of about 40 m^2 is allotted to the carpenter's workshop (see section 16.5), which is slightly smaller than an average-size workshop but the manning and the equipment proposed would enable the fulfilment of the average workshop's objectives.

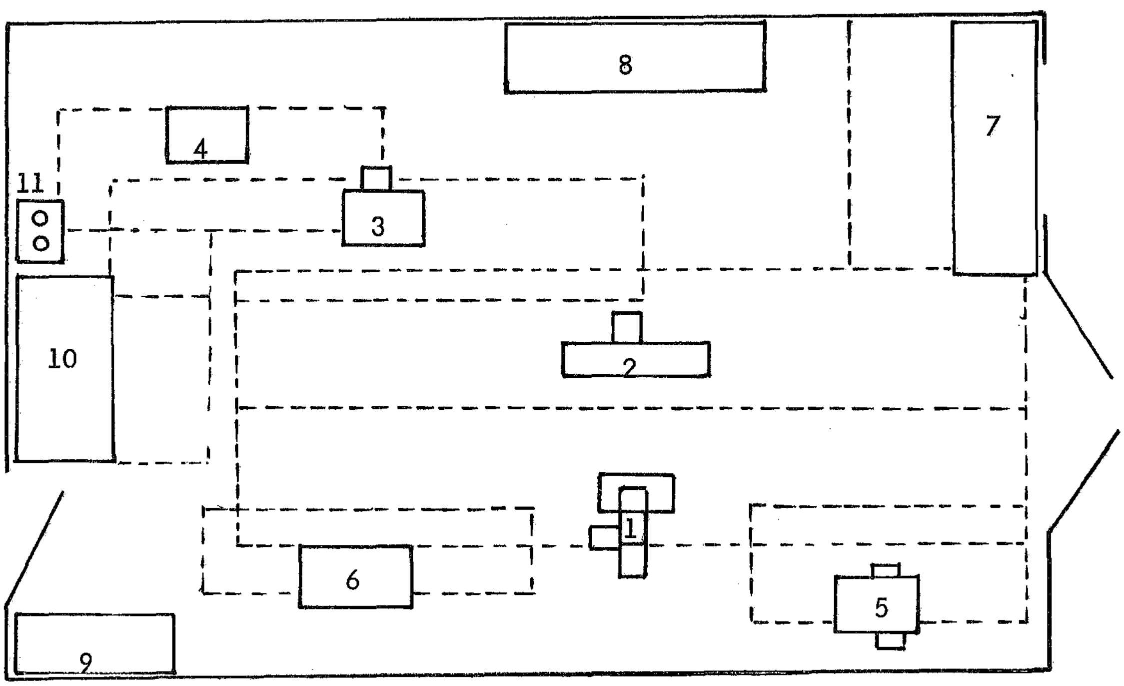


Figure 198 - Example of a carpenter's workshop equipment layout

The carpenter's necessary machine-tools are listed, their layout being shown in Figure 198:

(1) band saw, medium size, having the following approximate characteristics:

. maximum sawing height	260 mm
. distance between band and frame	380 mm
. height of table (with slewing arrangement)	950 mm
. band-wheel revolutions	750 r.p.m.
. motor speed and power	1 424 r.p.m., 1 kW
. approximate weight	300 kg

(2) planer

. table width and length	260 and 1 200 mm
. adjustable fence	
. cutting shaft	2 blades
. cutting shaft speed	6 000 r.p.m.
. motor power	1.5 kW
. approximate weight	350 kg

(3) thicknesser

. table width	260 mm
. maximum work-piece thickness	160 mm
. chip thickness	3 mm
. feed rate	8 m min^{-1}
. motor power	2 kW
. approximate weight	350 kg

(4) circular saw

. saw diameter	300 mm
. maximum cutting height	85 mm
. shaft speed	3 000 r.p.m.
. motor power	1.5 kW
. approximate weight	250 kg

(5) driller

. maximum drilling diameter	15 mm
. transverse table motion	125 mm
. longitudinal motion	160 mm
. vertical travel	100 mm

- drill speed 6 000 r.p.m.
- motor power 1.1 kW
- approximate weight 250 kg

(6) moulder

- table dimensions 750 x 450 mm
- spindle diameter 30 mm
- spindle speed 3 000/6 000 r.p.m.
- spindle vertical stroke 130 mm
- motor power 1.5 kW
- approximate weight 320 kg

In addition, the following workshop items and tools are necessary:

(7) joiner's work-bench, with front and back press;

(8) tool cupboard;

(9) overalls cabinet;

(10) work-bench for gluing;

(11) glue boiler, glue pot and brush; hand-operated belt-sanding machine; transport trolley.

Measuring instruments include set-square, bevel protractor, marking gauge, divider, metal ruler. Hand-tools include smoothing plane, polishing plane, double plane, jack plane, grooving plane; round-rasp, half-round rasp, flat-rasp; joiner's hammer, round mallet; keyhole saw, mitre block with tenon saw, bow saw; set of joiner's chisels; set of large and medium joiner's clamps; brace, brace-bits (centre, expanding); pliers (combination, pincers) screwdrivers.

This is virtually the classic outfit of a joiner's workshop designed for work on wood of all kinds, although the use of plastic materials is becoming more and more routine and a few more bench-top appliances and motor-driven tools would be necessary for work on synthetic materials, i.e. bench-top piston saw; bench-top circular saw (revs and blade for use with synthetics), as well as plastic glues and cold polymerizing synthetics.

A crew of two - a carpenter and an assistant - are assumed to work in the carpenter's workshop discussed.

The painting/drying space may be considered as a part of the carpenter's workshop, although it is used by all workshop units discussed thus far.

The chief items of equipment in this sub-unit are:

- Compressor, single-stage, single cylinder, 8 kg cm^{-2}, 5 l s^{-1}, 1.2 kW;
- Rubber pressure hose;
- Spray-gun with accessories;
- Paint and solvent containers, filtering funnel;
- Variable-height, swivel table, 1 m^2 area;

- Hot-air blower;
- Drying cabinet, 0.8 m^3 usable volume, 2 kW heaters, temperature-controllable.

The day's supply of solvents and the week's supply of paints are kept in a metal cabinet in the anteroom of the sub-unit; brush- as well as spray-painting are assumed to be one of its activities.

One man, trained on-the-job, could cope with the workload of this sub-unit, assisting the carpenter whenever necessary.

16.12 The mobile workshop

For meteorological purposes, the mobile workshop (Figure 199) is one installed in a truck designed for maintenance and repair activities in the difficult conditions of far-flung stations. Depending on the prevailing road conditions where it will be used, the truck may have either a conventional rear-wheel drive or a four-wheel drive.

The general features and equipment of a mobile workshop include the capacity to be self-sufficient in the intended scope of activities coupled with the ability to reach the remotest station within a reasonable time. It should be noted that the maintenance and repair of out-station equipment can be accomplished satisfactorily without the use of a mobile workshop, by replacing or returning the equipment to the maintenance centre for repair. However, this requires time and a decision has to be made whether or not the saving in "down time" justifies the provision of a mobile workshop.

If the mobile-workshop approach to maintenance is favoured, then a proper choice of vehicle, equipment and personnel should be considered. In connexion with this, two important questions must be answered:

(a) Is a general-purpose mobile workshop or a specialized one required?

(b) Is the mobile workshop intended to be used in relatively good road conditions, or (also) in off-the-road conditions?

The general-purpose mobile workshop for meteorological applications will have a wider scope of maintenance activities (mechanical, electrical, electronic, conventional meteorological instruments) but a more limited maintenance potential in any one of the task areas. Due to its wider range of objectives, a greater number of service instruments and equipment will be taken on service trips, which means a larger (perhaps slower) and more expensive vehicle. On the other hand, the special-purpose mobile workshop (e.g. one designed only for airport meteorological instrument maintenance and repair) would have a more limited scope of application, but better performance characteristics, as far as the task area is concerned. The special-purpose mobile workshop would normally be accommodated in a smaller, cheaper and faster vehicle. The alternatives should be considered carefully, in their long-term perspective, from the technical as well as the economical point of view.

The use of the mobile workshop in relatively good road conditions means that the vehicle used could be a conventional one, easier to find on the market, cheaper to buy and less expensive to run. Its use, however, would be confined to inhabited areas interconnected by a road system. If operation of the mobile workshop is also intended in off-the-road conditions, a four-wheel drive vehicle will be preferable (a four wheeler or a six-wheeler depending on the desired size).

Once the basic type of vehicle has been decided, the following more important vehicle characteristics have to be considered:

(a) Dimensions;

(b) Performance;

(c) Technical characteristics of engine and body;

(d) Workshop-equipment outfit and layout.

The potential user of a mobile workshop should be aware that there are two alternatives to acquiring the desired mobile unit: to buy it complete with outfit or to equip a suitable vehicle himself.

A number of mobile workshops of general utility are available on the market at present. Typical characteristics of one off-the-road, high-performance, mechanical mobile workshop, accommodated in a large van, are as follows:

(a) Dimensions: length - 4 015 mm; width - 1 680 mm; wheel-base - 2 100 mm; weight - 2 500 kg;

(b) Performance: four-wheel drive, maximum load - 925 kg; maximum speed - 115 km h^{-1}; cruising speed - 80 km h^{-1}; minimum speed - 2.8 km h^{-1}; turning circle diameter - 10.8 m; ground clearance - 285 mm; belly angle - 134^{o}; approach angle - 39^{o}; climbing ability - 42^{o}; fording depth - 700 mm;

(c) Technical characteristics: 82 h.p. petrol engine; sheet-steel body, self-supporting, non-walkable roof, double tail-gate; internal electrical installation 220 V/2 500 W fed from a petrol-motor-driven electrical a.c. generator; interior - several hatches with drawers, some of them divided into smaller sections for small tools, bolts and nuts; pull-out table;

(d) Workshop equipment: mechanic's box containing sets of hand-tools, electrical welding equipment (27 V/35-170 A), petrol-motor-driven (9 h.p., 6 500 r.p.m.) 200 kg winch, hand-machine tools, pull-out vice, etc.

A similar "special" mobile workshop, equipped for work in the field of electronics is also available on the market.

Another, of more general use, is the combined, mechanical, electrical and electronics mobile workshop, its outer appearance being illustrated in Figure 199. This is a mobile workshop based on an ordinary four-tonne truck. Its characteristics are as follows:

(a) Dimensions: overall length - 6 600 mm; width - 2 400 mm; empty weight - four tonnes; length of usable space - 4 420 mm; width - 2 320 mm; height = 1 950 mm;

(b) Performance: (on-the-road conditions) cruising speed - 90 km h^{-1}; maximum load - 2 000 kg;

(c) Technical characteristics: diesel engine; sheet-steel reinforced body with a walkable roof and a large roof luggage-rack; double tail-gate, lower part of the side windows can be pulled down to open; forced ventilation of the workshop space; oil-heating 25.14×10^4 J h^{-1} ; lighting 220 V a.c. (emergency 24 V); power sockets - two three-phase 380 V, four monophase 220 V; total power rating 4 kW; power source - petrol-driven electrical a.c. three-phase generator.

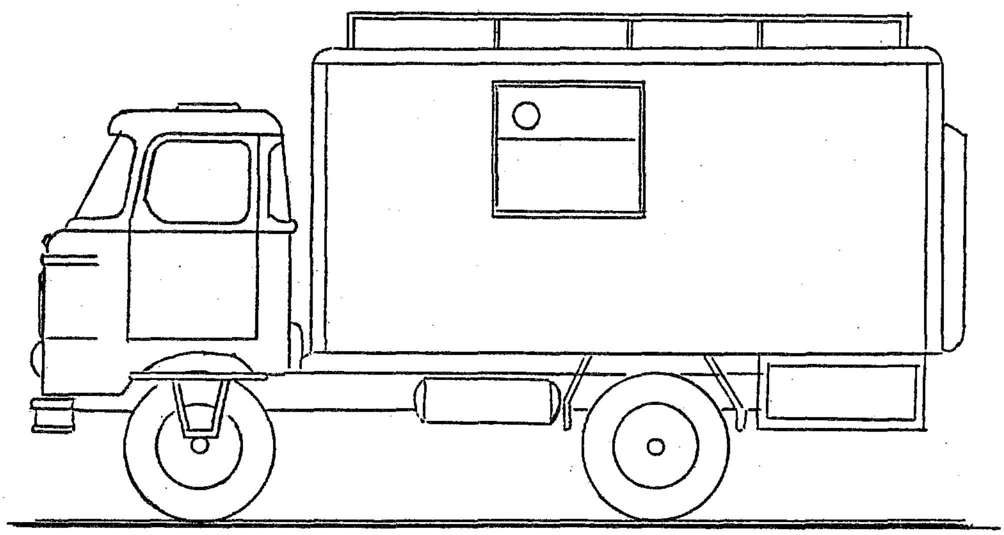


Figure 199 - Exterior of combined mobile workshop

A 16 m^2 tent for out-door work can be fastened to the luggage-rack rail, at its rear side, supported by two front steel-pipe posts.

An open-top luggage trailer can be used to transport bulky equipment to the central workshop for repair.

Mechanical equipment consists of: gas-welding equipment, together with steel acetylene and oxygen cylinders and accessories; turning lathe (400 mm between centres); bench-top drill (450 W); bench-top grinder (250 W); mechanic's box containing set of miscellaneous hand-tools; folding work-bench for outdoor work; ladder; portable air-compressor, 8 kg cm^{-2}, 2 l s^{-1} , 0.5 kW; combined propane/butane burner gas-cylinder; folding lifting tripod, pulley block and rope (lifting capacity - 400 kg).

Electrical equipment consists of: three-phase, 380 V/4 kW, petrol-engine-driven electrical generator, (in an outside pull-out cabinet); storage batteries 24 V/85 A h^{-1}; ampere-ohm-volt-meter, transistorized volt-/ohm-meter; RLC bridge; transistor tester; oscilloscope (battery driven); sine-/square-wave signal source; soldering equipment; resistor/capacitor stock, electronics-technician hand-tool kit; voltage source stabilized, adjustable, maximum 24 V/2.5 A.

On trips to repair special field equipment, additional tools and measuring instruments are borrowed from the central workshop.

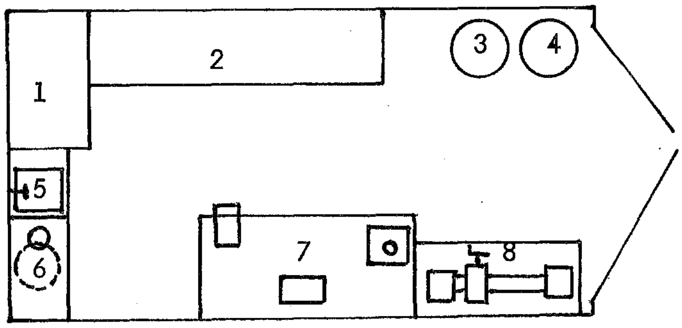


Figure 200 - Interior of combined mobile workshop: 1 - cupboard; 2 - electrical work-bench; 3 - acetylene and oxygen and 4 - gas cylinders; 5 - water sink; 6 - propane/ butane gas cylinder and burner; 7 - mechanic's work-bench; 8 - turning lathe

A crew of three staff the mobile workshop: a professional (engineering degree), a technician and a driver. The booth of the truck accommodates three people on trips. Two folding berths are available inside the workshop area for longer stays in the field.

The mobile workshop is provided with a two-way radio for communication with headquarters.

CHAPTER 17

METEOROLOGICAL INSTRUMENT CALIBRATION LABORATORIES AND ROUTINES

17.1 Calibration laboratories - general

In order to read the correct values of meteorological variables, meteorological instruments should be compared with the relevant standard instruments and their respective scales corrected accordingly, before their release for operational work. The procedure of comparing and making an instrument's scale compatible with that of the standard instrument is known as calibration.

Generally, a meteorological instrument does not hold its calibration permanently. In varying degrees for different meteorological instruments, the calibration tends to change with time and the compatibility between the scales of the measuring instrument and the standard instrument is ruined. These changes may be abrupt or gradual, but in all cases they lead to faulty meteorological measurements.

The responsibility for the accuracy of meteorological observations and their spatial and time comparability lies with the meteorological inspection and the meteorological instrument calibration laboratories. While the inspection has a controlling function aimed at preserving the internationally accepted standards for meteorological observations, the laboratories take care of the operational condition of the meteorological instruments. Control of the observation routines and the immediate care of the meteorological instruments are complementary functions in the process to obtain high-quality meteorological data but they are purposefully placed in different administrative units so as to maintain a high working efficiency for each of them.

The calibration laboratories, being entrusted with the immediate care of the proper working conditions of the meteorological instruments, have to perform the following duties:

(a) Carry out periodically, according to schedules, field and laboratory tests of the calibration characteristics of meteorological instruments, in order to establish their operational performance;

(b) Carry out comparisons between meteorological instruments and the respective standard instruments in order to establish the nature and magnitude of the deviation of the instruments' calibration from accepted normals;

(c) Re-calibrate any instrument whose calibration has drifted beyond the accepted normals;

(d) Take care of the standard meteorological instruments and laboratory calibration equipment and continuously improve laboratory practices;

(e) Extend calibration and meteorological control over newly introduced meteorological instruments, as well as those used in research.

In order to be able to fulfil their objectives, the calibration laboratories need the appropriate instruments/equipment, personnel and organization of activities.

17.2 Layout of the calibration laboratories (general) - interaction with other branches dealing with meteorological observations and instruments

Following the concept of standard workshop and laboratory design, a possible layout of the calibration laboratories is given in section 16.5 and illustrated in Figure 166. Various other arrangements in this respect may be equally acceptable, provided certain fundamental requirements concerning their performance are observed:

(a) Preservation of high meteorological standards;

(b) Observation of the obligatory precautionary measures against work-hazards;

(c) Arrangement promoting the most functional and efficient movement of people and instruments.

Figure 165 of section 16.5 presents the major inputs to the calibration laboratories within the framework of the technical branch. It should be added that, in its daily routines, the calibration laboratory's responsibilities are spread over the two main areas of meteorological activities: operations and research.

Concerning operational activities, a two-way relationship exists between the maintenance and repair workshops and the meteorological network and inspection. In addition, the activities of the calibration laboratories are linked to those of outside institutions, such as the national bureau of standards and non-meteorological users of meteorological equipment.

As regards research, the calibration laboratories' activities are linked to those of the Meteorological Service and outside institutions through the laboratory and field-research experiments.

To those contributing to the work of the calibration laboratories should be added the laboratory itself, with its activities aimed at increasing and improving its own potential. These activities are connected mainly with the upkeep of laboratory equipment and instruments and methodological and technological improvements of the calibration routines.

17.3 Working conditions and safety considerations

Before being received for calibration by the laboratories, the incoming meteorological instruments undergo a pre-calibration preparation:

(a) Examination for defects, filling-in of the accompanying statistical forms of the MIMW files;

(b) Cleaning, necessary re-painting of weather-exposed parts;

(c) Oiling, necessary repair.

The meteorological instruments to be calibrated should be brought to the laboratories in good physical condition. With the exception of mercury barometers, the pre-calibration preparation should be undertaken in the maintenance workshops. The mercury barometers' pre-calibration (pre-comparison) preparation is the responsibility of the mercury laboratory and filling station.

The obligations of the calibration laboratories defined in this way enable the maintenance of the necessary working conditions in terms of climate and cleanliness: the temperature and humidity conditions inside the calibration laboratories should be kept within the limits of the widely-accepted office climate; special measures should be taken in hot and arid climates for proper air-conditioning, while adequate heating should be guaranteed in cold climates; overalls should be provided and rules of work and cleanliness should be observed. Adequate task lighting should be provided, preferably "cold" lighting inside thermo- and hygro-chambers.

An increased rate of ventilation should be provided for the mercury laboratory, with the air being aspirated through the ventilation duct near the floor and expelled at a distance from the building. If mercury is spilled, it should be dusted with sulphur powder, swept up and disposed of without risk of contaminating the environment.

The work of the calibration laboratories involves certain hazards, e.g.:

- Work with open-surface inflammable liquids, such as alcohol;
- Work with coolants such as liquid nitrogen and solid carbon dioxide;
- Work with mercury.

The observation of fire regulations should be strict and suitable fire-extinguishing means placed in conspicuous places. All electrical appliances, instruments and equipment should be properly earthed.

Working schedules for personnel working in the mercury laboratory should be designed so as to prevent long-term exposure to hazardous vapours. Periodical medical checks should be compulsory.

17.4 Personnel - qualifications

The operational activities of the calibration laboratories are fairly routine and repetitive. Well-qualified and experienced technical personnel will need little guidance from professionals in order to carry out the operational work. However, activities connected with testing, comparison and calibration of new models of conventional meteorological instruments and, especially, the handling of special-purpose experimental equipment and instruments for research purposes, may pose problems which require the assistance of a professional.

It is impractical to give general prescriptions in respect of the number and level of technicians and professionals in the calibration laboratories, as this depends on the actual workload and locally-established working habits but, in considering the staffing of the laboratories, it should be borne in mind that a number of testing and calibration operations require the co-operation of two persons, which would seem to be the basis on which to determine the personnel in each laboratory but, if the workload permits, a smaller number of people from different laboratories may be regrouped temporarily to meet the current requirements of a specific calibration operation.

The number of professional staff will also depend, within certain limits, on the workload. The minimum number, however, accounting for the necessity of guidance and training, seems to be three: one professional, responsible for the atmospheric-pressure laboratory; one for the temperature and humidity and anemometry laboratories; and one for the solar-radiation laboratory.

The qualification levels for the personnel of the calibration laboratories is suggested in the following table:

Laboratory	Qualifications of technical staff	Qualifications of professional staff	In-service training	Supervisor
Atmospheric pressure	Meteorologist Technical school level	Meteorologist University level	6 months	B.Sc.
Temperature/ humidity	Meteorologist Technical school level	Meteorologist University level	4 months	B.Sc.
Anemometry	Meteorologist Technical school level	Meteorologist University level	4 months	B.Sc.
Solar radiation	Electronic technician	Physicist/ electronics engineer	1 year	B.Sc.

The solar-radiation laboratory is staffed by electronic technicians as contemporary solar-radiation instruments are linked with recording and integrating devices which require competent handling. It is assumed that an electronics technician would absorb the necessary meteorological on-the-job training more quickly than a meteorological technician would gain the necessary electronics expertise.

17.5 Periodic and non-periodic activities

Activities in the calibration laboratories may be divided into two major groups: periodic and non-periodic (i.e. of sporadic nature).

Periodic activities are connected with maintenance cycles of network meteorological instruments. For a number of instruments, the periodicity of these activities is reflected in section 16.4. The maintenance cycles shown there in tabular form could be used as a guide in the matter, bearing in mind the effect which environmental conditions might have on them and on the nature of the most frequent instrument failures. In a jungle environment, instrument performance will be affected by humidity and wildlife; in a desert by sandstorms; in moderate latitudes by atmospheric pollution; and in polar conditions by low temperature and snow, etc.

While maintenance cycles may be shortened or extended according to environmental factors (as far as the majority of station instruments are concerned), special attention should be given to the periodic testing and comparison with standard instruments of atmospheric-pressure measuring instruments.

Non-periodic calibration activities are connected with instruments which have been repaired after a failure and are submitted for re-calibration. To this group belong activities connected with newly-issued instruments which have been kept in storage for a prolonged period of time.

As a rule, meteorological instruments subjected to any repair, however small, should be tested under laboratory conditions. The test is aimed at discovering whether the original calibration holds and, if not, the nature of the change: whether it is connected with a mere translation of the calibration curve or a rotation or both.

With instruments having linear response to the measured variable, the cases of translation of the calibration curve can be remedied, if the error is within the limits prescribed, by readjustment.

In all cases in which the error shows a tendency to increase - or decrease - within the instrument's scale limits (a rotation of the calibration curve is indicated), re-calibration is necessary.

New instruments should be tested under laboratory conditions before dispatch to the field station.

Normally, the periodic activities of the calibration laboratories represent the bulk of laboratory work. In planning this work, allowance should be made for the non-periodic activities, including those connected with the meteorological instruments of outside institutions.

17.6 Atmospheric-pressure laboratory

17.6.1 Calibration and testing equipment

Instruments for the measurement of atmospheric pressure are of great importance to meteorology for the purposes of weather forecasting and aviation. Control over the operational condition of pressure-measuring instruments, checking their accuracy, comparison and calibration, are the main objectives of the atmospheric-pressure laboratory (APL).

The equipment and instrumentation of an APL depend largely on the scope of the activities performed and the accuracy requirements of the pressure-measuring instruments dealt with. The following main fields of activity of an APL may be listed:

(a) Control over the surface meteorological stations' pressure-measuring instruments;

(b) Control over upper-air measuring instruments;

(c) Control over pressure-measuring instruments used by non-meteorological (e.g. marine, industrial, geological, gravimetric, etc.) organizations.

The accuracy requirements pertaining to various pressure-measuring instruments vary considerably, depending on their application:

- In industry: 0.6 - 4 per cent;
- In meteorology (surface, upper-air, aviation): 0.015 to 0.1 per cent;
- Science and metrology: 0.005 to 0.01 per cent.

As far as meteorology is concerned, the fundamental pressure-measuring instrument may be considered to be the mercury barometer, followed by the aneroid barometer, based on the use of an aneroid-pressure capsule sensor.

Various pressure-measuring instruments are used in the national Meteorological Services. A code letter is accepted for each category:

- A - Primary or secondary standard barometer capable of independent determination of the atmospheric pressure to an accuracy of at least $\pm$ 0.05 hPa. Such a barometer, selected by regional agreement as a regional standard, will be coded A_r;

- B - Working standard barometer of a design suitable for routine pressure comparisons and with known errors (established by comparison with a primary or secondary standard barometer). If used for regional comparison purposes, when no A_r standard is available, this category of barometer will be indicated as B_r;
- C - Reference standard barometer used for comparison of travelling standard and station barometers at field supervising stations of a national Meteorological Service;
- S - Mercury barometer located at an ordinary meteorological station;
- P - Mercury barometer of good quality and accuracy, which may be carried from one station to another and still retain its calibration;
- N - Portable precision aneroid barometer of first-class quality;
- M - Portable microbarograph of good quality and accuracy.

The atmospheric-pressure measuring instruments used in operational work and subject to current meteorological control are as follows:

(a) Mercury barometers:

(i) Fortin type;

(ii) Contracted-scale type;

(b) Aneroid barometers (approximate measuring range: 1 064 hPa - 800 hPa), aneroid altimeters (1 064 hPa - 600 hPa):

(i) Aneroid pressure-measuring instruments having analogue read-out;

(ii) Aneroid instruments having increased accuracy and a digital read-out;

(c) Barographs (approximate total measuring range: 1 064 hPa - 800 hPa in sub-ranges of several hundreds of hectopascals):

(i) Field barographs, 100 hPa range of scale within the total measuring range indicated above, with or without adjustable range shift and with daily or weekly rotation of the recording drum;

(ii) Microbarographs, 66 hPa/50 mm scale, or similar, of an expanded resolution (up to 5 mm scale division per hectopascal), increased accuracy;

(d) Hypsometers (thermobarometers), surface measurements (down to 700 hPa), upper-air (the radiosonde pressure range);

(e) Radiosondes (pressure range: 1 050 - 5 hPa).

In order to be able to carry out comparison, testing and calibration procedures on the pressure instruments listed above, the laboratory should be in possession of the following control and standard instruments:

(a) Standard barometers, category A or B, but not lower than C ($\pm$ 0.05 hPa);

(b) Travelling standard barometer, category P;

(c) Aneroid barometer category N (preferably one of increased accuracy, digital type);

(d) Open-scale barograph (adjustable within the 1 064 hPa - 800 hPa range);

(e) Microbarograph, category M;

(f) Test-chamber aneroid barometer;

(g) Test-chamber mercury barometer (5 - 1 080 hPa).

A range of pressure-testing equipment will be used, such as:

(a) Glass pressure-bell and vacuum pump (10^{-2} mm Hg vacuum);

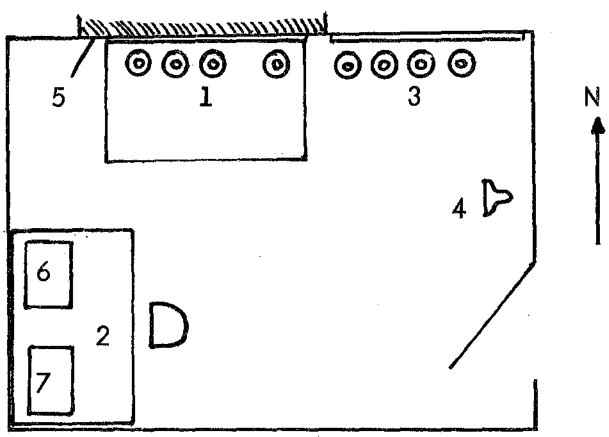
(b) Pressure cabinet and vacuum pump (10^{-2} mm Hg);

(c) Pressure chamber with pressure hood for accommodation of tested mercury barometers - vacuum pump of increased capacity;

(d) Thermo-baro chamber (suitable for testing upper-air instruments) with remote-reading thermometers (-70° to + 100°C), vacuum pump of increased capacity, refrigeration compressor, heater.

17.6.1.1 Mercury barometers

The mercury barometers for laboratory use are kept, with the exception of the various pressure-chamber test barometers, separately, preferably in a basement room. The standard barometers are hung on a north-facing cement wall which has a heavy cement foundation (against vibrations). A cabinet with a glass door is used to accommodate the standard barometers (Figure 201). Ample space is provided inside the barometer cabinet for the tested barometers as well. Suitable lighting, preferably cold type, should be available inside the cabinet, installed in such a way as to ease the operator's reading of the instrument.



(1) standard-barometer cabinet;
(2) operator's desk;
(3) mercury barometers awaiting comparison;
(4) ventilator;
(5) cement reinforcement of the wall;
(6) microbarograph;
(7) barograph, weekly rotation

Figure 201 - Standard-barometer room

The standard-barometer room should be windowless and the north-facing wall should be an external wall of the building. The temperature inside the room should be kept as constant as possible. A small electric fan may be used against possible temperature stratification. The barometer cabinet may be connected to the outside air by a special hose and static head, a useful arrangement in countries with prevailing windy conditions.

Usually, complicated and expensive high-accuracy absolute standard barometers are used by the meteorological institutions of the country (bureau of standards). The Meteorological Services use improved-accuracy mercury barometers of high-calibration stability as standard instruments.

The operating principle of the mercury barometer is discussed in the section dealing with barometry. A brief mention will be made here of certain basic facts:

The fundamental equation of the mercury barometer is as follows:

$$P_1 - P_2 = H.g.\rho$$

where:

P_1 = ambient pressure;

P_2 = pressure inside the Torricellian vacuum of the barometer;

H = height of the mercury column of the barometer;

g = gravity acceleration;

ρ = the barometric-liquid (mercury) density.

Assuming that $P_2 = 0$ (in fact, the mercury-vapour pressure at the temperature of measurement has a negligibly small value), the above equation is simplified.

The total measurement error is obtained from the expression:

$$\Delta P_1 = (\delta_h + \delta\rho + \delta_g)P_1 + \Delta P_2 + \Delta P_k$$

where:

δ_h = relative error of measurement of the height of the column;

$\delta\rho$ = relative error of determination of the mercury density;

δ_g = relative error of determination of the gravity acceleration;

ΔP_2 = error in the determination of the pressure inside the Torricellian vacuum;

ΔP_k = error stemming from capillary phenomena.

The accuracy of "static" mercury standard barometers may reach figures better than 0.013 hPa.

Less sophisticated, but more convenient to use, are the mercurv barometers of the syphon-cistern type, one type of which is the pre-war Fuess model. The principle of this barometer is illustrated in Figure 202.

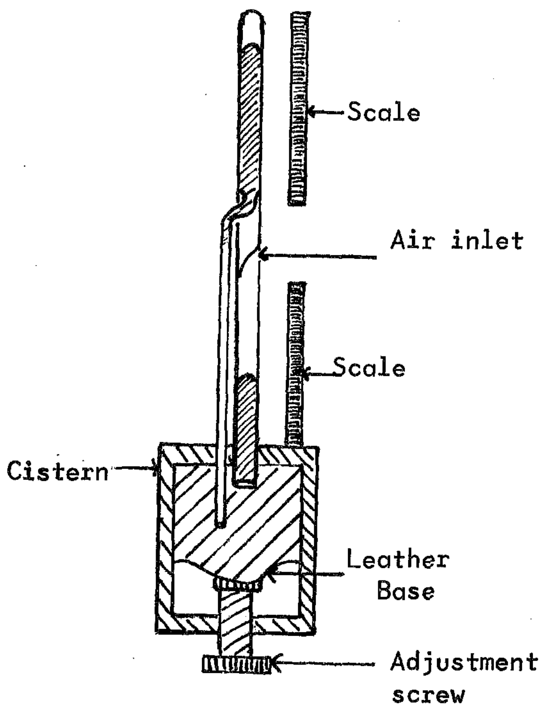


Figure 202 - Fuess standard barometer

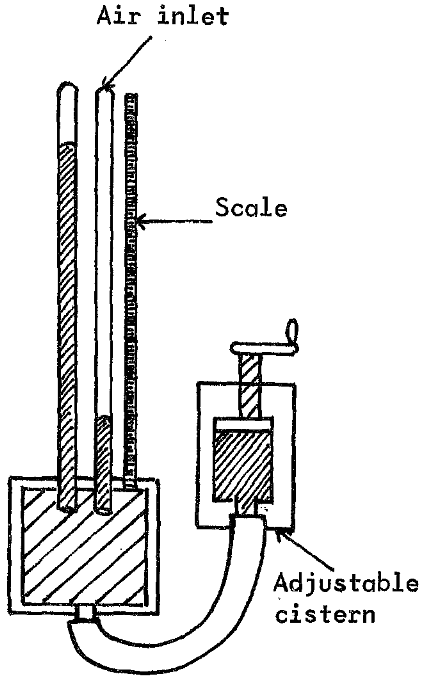


Figure 203 - The MBP barometer

Two glass tubes, one closed at the top, the other (shorter) opened, are fastened to a cistern, provided with a leather base and an adjusting screw. The syphon barometer thus obtained is filled with mercury and the pressure values are read out as the difference in mercury levels inside the two tubes. Two optical verniers add to the accuracy of the readings of the positions of the two mercury menisci, the overall accuracy being 0.065 hPa pressure value. The large-bore barometric tubes keep the capillary error within reasonable limits.

A slightly different model is the MBP barometer (U.S.S.R.), based on a similar principle of operation (Figure 203). It consists of two 18-mm bore tubes, one closed at the top, the other open, connected at their lower ends through the cistern of the barometer. The cistern has a nipple at its lower end through which its volume is connected by a plastic hose to the volume of an adjustable-height mercury reservoir, which helps bring the mercury level inside the closed tube to a fixed datum level before the pressure is read.

As in the Fuess type, the atmospheric pressure is read out against a scale as the difference between the levels of the mercury menisci in the two barometric tubes of the syphon. The overall accuracy may attain 0.065 hPa.

Although the two barometers described above are, strictly speaking, not a static type of instrument, their accuracy can only be assured if they are permanently installed.

The travelling standard barometers are ordinary barometers of large-bore tubes, capable of retaining their index of correction to within 0.1 hPa. They are provided with special spring-suspension portable boxes.

The test-chamber mercury barometers are also of ordinary design, except for the expanded scale (5 hPa - 1 080 hPa) and the cistern nipple for connexion of the cistern air-inlet to the volume of the chamber. Accuracy is about 0.1 hPa.

A brief discussion of the basic pressure-measuring instruments' testing equipment follows.

17.6.1.2 Aneroid barometers

One of the simplest devices used in testing pressure sensors and aneroid barometers is the pressure bell (Figure 204). A transparent glass, with a smooth and polished rim, confines the space within which the pressure instruments are tested. The glass bell rests on a polished, thinly-greased steel surface, which carries the inlets for the test barometer, vacuum pump and atmospheric air. In addition, the steel plate may have sealed connexions for electrical remoting cables.

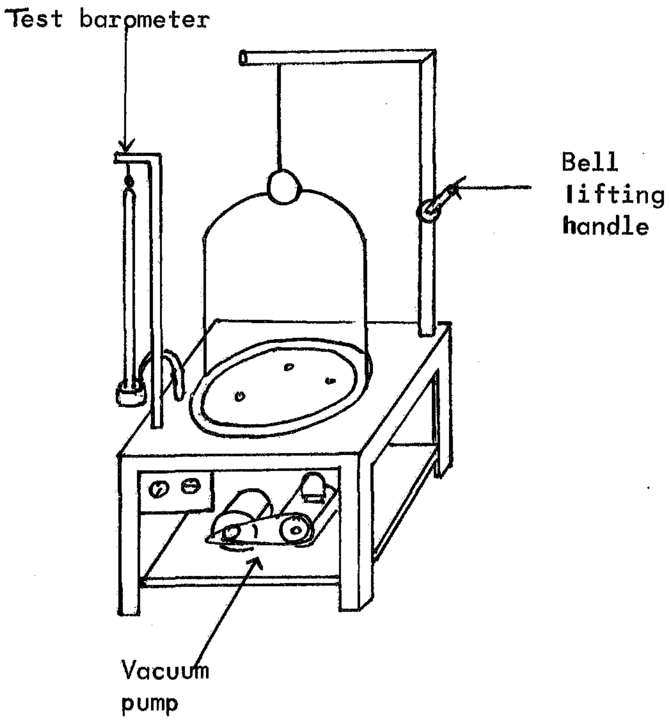


Figure 204 - Pressure bell

The space under the bell, connected to the vacuum pump of medium capacity (10^{-2} mm Hg vacuum at 1 000 r.p.m. of the pump; motor of approximate power rating 1 kW), can be subjected to a controlled evacuation of the air, the pressure being measured by the test barometer.

The range of pressures of the pressure bell are from ambient pressure down to 50 - 60 hPa. Pressure-bells are sensitive to shock: there is a danger of implosion at low pressures and if the glass bell is accidentally knocked by a heavy object.

17.6.1.3 Barographs

A pressure chamber of about 45 m^3 working space is shown in Figure 205. it is a versatile piece of equipment suitable for testing barographs and aneroid barometers at pressures lower than ambient, as well as slightly higher.

The vacuum and pressure are produced by the pump installed below the testing chamber. Vacuum and over-power pressure are produced in two steel cylinders and the volume of the chamber may be connected to the two cylinders (either to vacuum or to

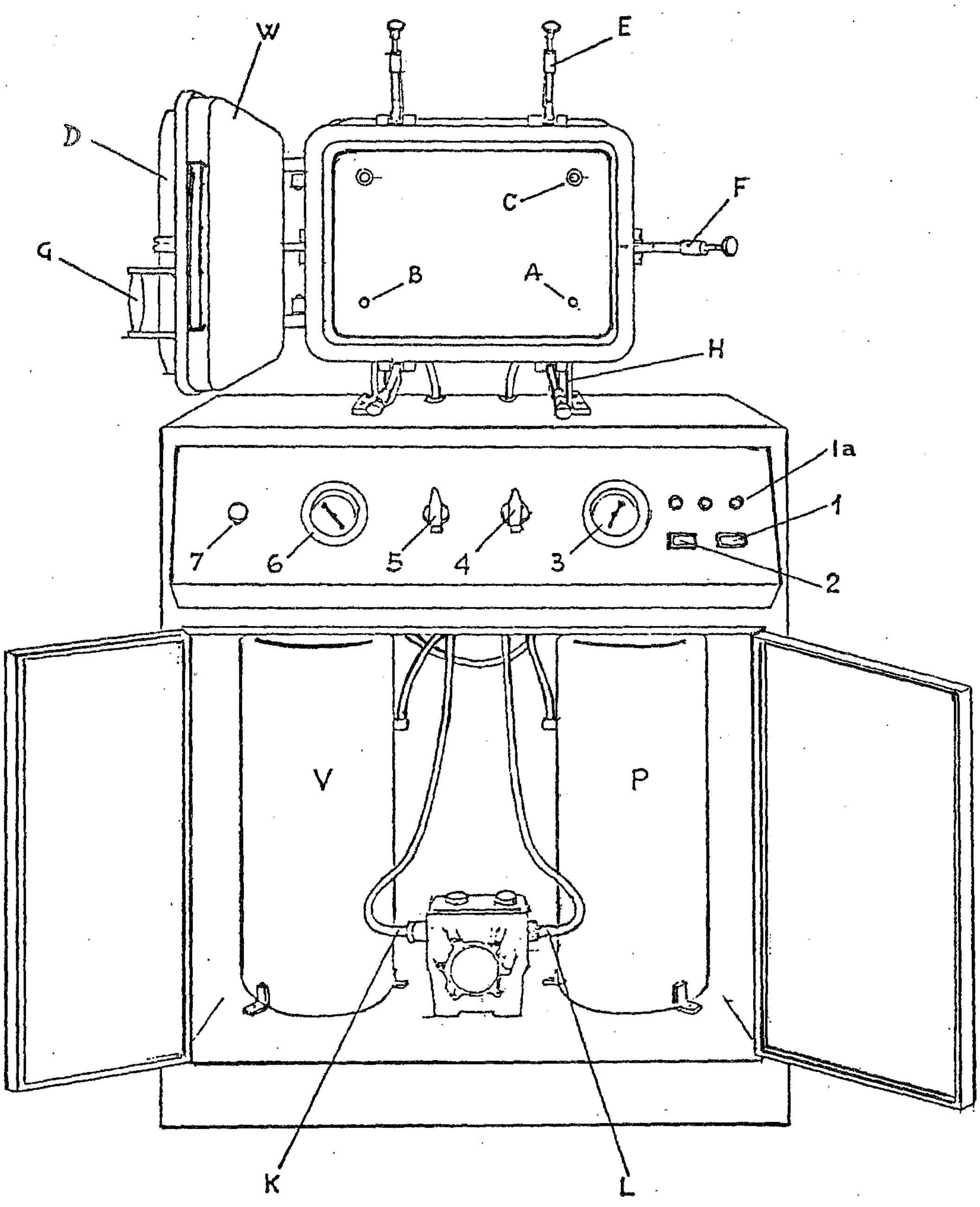


Figure 205 - Pressure chamber for testing barographs;

(1) main switch;
(2) pump push-button;
(3) pressure gauge 0 - 1 kg m^{-2};
(4) selector knob pressure/ vacuum connector to the pump;
(1a) line fuses;
(5) selector knob pressure/vacuum connector to the chamber;
(6) vacuum gauge 0 - 760 mm;
(7) bleed knob, pressure equalizer of the chamber.

A, B - inlet/outlet chamber openings;
C - hermetic, insulated electric leads;
D - door frame;
W - thick glass window;
G - door handle;
H - chamber support

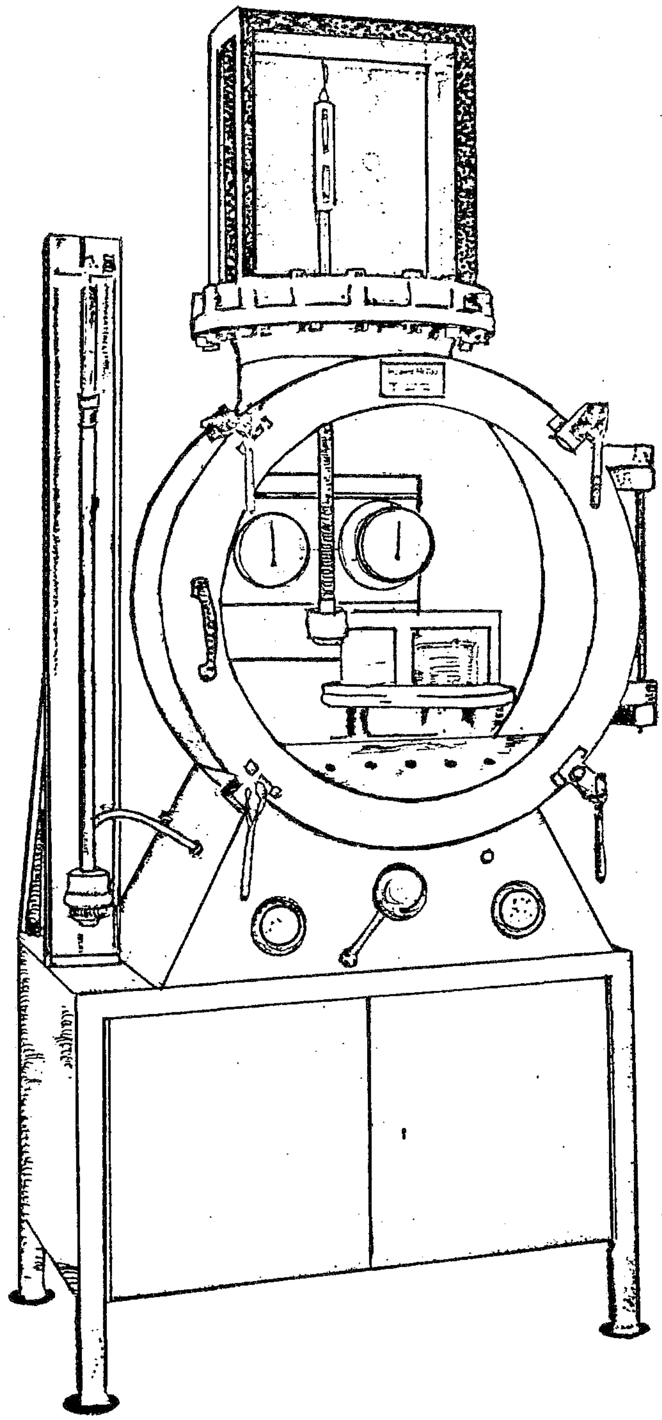


Figure 206 - Pressure-testing chamber with mercury-barometer testing hood

pressure) by two selector knobs (5), (4). Thus, fast excursions between the extremes of pressure can be established inside the testing space for the purpose of "massaging" the pressure sensors prior to actual calibration. The pressure or vacuum can be read-out on the pressure-gauge (3), (6) or the vacuum-gauge. The return to ambient pressure is obtained through the bleed knob (7).

The chamber is provided with sealed go-through electrical leads for either remote measurement of the testing-space parameters or control of the instruments under test (time-mark indication).

A larger model of a pressure chamber suitable for testing aneroid as well as mercury barometers is shown in Figure 206. Its working space is about 190 dm^3, large enough to accommodate several barographs and aneroid barometers. An acryl-glass hood enables several mercury barometers to be tested as well. The vacuum inside the testing space is established with the help of a two-stage gas-ballast pump within the operational limits of the pressure scale of the tested instrument. Either a mercury barometer with its cistern connected by a plastic hose to the test space of the chamber or an aneroid barometer inside the testing space and readable through the heavy glass door of the chamber can be used as a control barometer. The power consumption of the chamber will depend mainly on the vacuum pump used and the motor arrangement but will be around 1.5 kW.

A test chamber of a more specialized application is the thermo-barochamber, which is schematically presented in Figure 207.

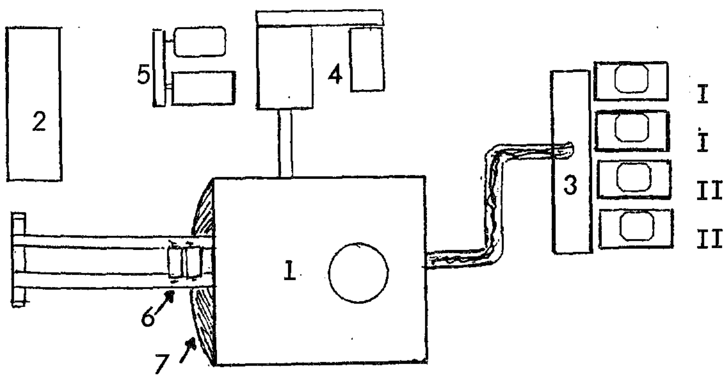


Figure 207 - View of the combined thermo-baro testing chamber from above: (1) armoured body of the thermo-baro chamber; (2) control swith-board; (3) three-stage cooling compressor; (4) vacuum pump; (5) hydraulic pump (for opening the lid); (6) pressure-lid carriage; (7) pressure-lid

The specifications of the thermo-baro testing chamber are as follows: testing space - 500 dm^3; temperature range - -70 to + 100°C; pressure range - ambient to 2 hPa; total power consuption - 40 kW; installation space - 5 x 10 m.

The thermo-baro chamber is suitable for checks of different pressure-measuring instruments at various pressure values and temperatures. In this respect it is well suited for the testing and calibration (partial) of radiosondes, as well as other sensors.

17.6.2 Standard instruments and routines

As has already been mentioned, the APL should take care of the testing, comparison and calibration of the meteorological-network pressure-measuring instruments, as well as of the safe-keeping of the standard instruments.

The care of the standard instruments consists of preventive maintenance and periodic comparison of these instruments with an established standard on a regional scale. The comparisons are carried out by well-trained observers, making use of travelling standard barometers. Selected mercury barometer of large-bore tubes, capable of retaining their calibration characteristics for prolonged periods of travel, are used as travelling standard barometers, category P. Provision for a check of the Torricellian vacuum of such barometers is an advantage. A second choice is the Fortin barometer with tube of 12 mm (or 9 mm) bore. Syphon-control barometers are also suitable.

Regional standard barometers are established in the following locations (see *Guide to meteorological instruments and methods of observation* (WMO-No. 8)).

Region	Location	Category
I	Cairo, Egypt	A_r
	Casablanca, Morocco	A_r
	Dakar, Senegal	A_r
	Douala, Cameroon	A_r
	Kinshasa/Binza, Zaire	A_r
	Nairobi, Kenya	A_r
	Oran, Algeria	A_r
II	Calcutta, India	B_r
III	Rio de Janeiro, Brazil	A_r
	Buenos Aires, Argentina	B_r
	Maracay, Venezuela	B_r
IV	Washington, D.C. (Gaithersburg, Md.) U.S.A.	A_r
	Toronto, Canada (sub-regional)	A_r
	San Juan, Puerto Rico (sub-regional)	A_r
	Miami, Fla., U.S.A. (sub-regional)	A_r
V	Melbourne, Australia	A_r
VI	London, United Kingdom	A_r
	Leningrad, U.S.S.R.	A_r
	Trappes, France	A_r
	Hamburg, Federal Republic of Germany	A_r

17.6.2.1 Mercury barometers

The mercury barometers are compared with a standard instrument according to the following programme:

(a) The national working standard, B, is compared with the primary or secondary standard barometer, A, through a travelling standard, P, once every two years. Travelling standard barometers may not be necessary if the compared A and B barometers are located at the same centre;

(b) The reference standard barometer, C, is compared with the national working standard, B, at least once every two years;

(c) The station barometer, S, is compared with the reference standard, C, at least once a year, by means of a travelling standard.

The following comparison procedures are applicable to barometers at different locations:

Auxiliary instruments used in the comparison are: two travelling standard barometers, category P, one aneroid barometer, category N and one microbarograph, category M.

A "closed-circuit" procedure is used in the comparison of the two instruments "1" and "2": the travelling standards P are carried from barometer "1" to barometer "2" and returned to "1", the auxiliary instruments - aneroid barograph, category N and microbarograph, category M, are carried together with the travelling standard barometer.

Before beginning the comparison, the travelling standard barometers, carried "cistern-up" in a special box, are removed therefrom, examined carefully, then brought to the normal measuring position according to the instructions and hung next to the barometer with which they are going to be compared. The air screw of the travelling standard is opened a few turns.

For standardization purposes, all instruments participating in the comparison are given equal exposure for at least 24 hours before comparison readings are started. The temperature of the room where the comparison is taking place should be kept as constant as possible.

For barometer-comparison readings, preference should be given to barometrically quiet periods, i.e. when pressure according to the recording instruments is "steady" or changing slowly (not faster than 0.65 hPa). The microbarograph should be used in establishing the pressure variability.

Comparison readings are taken in pairs as follows: temperature of first travelling standard, temperature of barometer compared, temperature of second travelling standard (if available). Then pressure readings of all three barometers are taken in the same order. After a while, temperature and pressure readings are taken of all three barometers but in a reverse order, starting with the second travelling standard.

At least five comparison readings should be taken for a category S barometer and at least ten readings for categories A, B, and C barometers, preferably at different atmospheric pressures.

The comparison records should contain all temperature readings, pressure readings corrected for gravity, temperature and instrumental error, data about wind speed and direction, wind gustiness, the actual elevation above sea-level of the barometer's zero point, the name of the station, its geographical co-ordinates and the date and time of the observations.

If readings of the aneroid barograph are taken, they also should be included in the comparison form.

The instrumental correction of the barometer compared is calculated on the arithmetic mean of the data of the comparison, taking into account the instrumental correction of the standard barometer for temperature difference between the temperatures of standard and compared barometers.

The comparison of the travelling standard barometers with the standard barometer, category A (or B or C), is carried out first before the departure for the location of the barometer category S (or else the compared barometer), and next the return from there. The two comparisons of the travelling standard must show reasonable agreement (maximum acceptable difference: 0.13 hPa). As far as practicable, all measurement discrepancies should finally be expressed with respect to a primary or secondary barometer reading of category A. This will assure a common base for all comparisons.

The final results of the comparison are reflected in a special certificate which is attached to the barometer compared.

17.6.2.2 Aneroid barometers

The testing and comparison of aneroid barometers are carried out according to the following programme:

The aneroid barometer is first examined carefully for the following defects: play of the indicating needle (maximum 0.5 scale division), equal distance between needle and dial at all parts of the dial, smooth running of the mechanical links of the gear, proper functioning of the thermometer attached, proper functioning of the adjustment screw, good general outer appearance (glass lid, body, hook for hanging). The results of the examination are entered in the established statistical form (failure statistics form).

The temperature correction of the instrument over at least two temperature ranges: $0^{\circ}C - 5^{\circ}C$ and $25^{\circ}C - 30^{\circ}C$ is determined. A box thermostat (or for that matter a simple ice chamber) may be used. The determination of the temperature correction of the instrument is carried out at the pressure of the laboratory and only if this varies by less than 6.5 hPa per 6 hours. The minimum temprature adaptation time for the instrument is taken to be 3 hours.

The temperature correction obtained by the previous procedure, $\Delta P/\Delta t$ is applied to all further test procedures using the formula:

$$P = \Delta P . t_1 + b(P_1 - P_2)(t_2 - t_1)$$

where:

P_1 = pressure at which the pressure correction Δp has been determined;

P_2 = pressure at the time of the actual observation;

t_1 = temperature of the aneroid barometer;

t_2 = temperature at which the pressure correction has been determined;

b = coefficient depending on the capsule material (order of magnitude 0.0005).

The instrumental corrections of the aneroid are determined at various values of the atmospheric pressure. A comparison is carried out between the aneroid barometer and the test mercury barometer under conditions of controlled pressure in the testing chamber. The multiple read-outs for a fixed pressure point are averaged.

The comparison results are plotted on a graph. The relative constancy of the correction (if any) within the test interval indicates the proper functioning of the instrument. The tests are carried out with a falling chamber pressure and repeated on the way back with a gradual increase of pressure until atmospheric pressure is reached. The scatter of pressure read-outs on the increasing-pressure leg of the calibration is expected to be greater than that of the decreasing one.

If the tested barometer correction is relatively constant within the test interval but remains greater than a scale division on the tested instrument's dial, the instrument is adjusted with the adjustment screw. The comparison procedure is repeated after the adjustment until satisfactory comparison results are obtained.

Erratic scatter of the instrument correction, both in sign and amplitude, from a comparison procedure which has been thoroughly carried out may be an indication of mechanical faults in the instrument. A steady change of the correction within the test interval may be an indication of a changed sensitivity. Both cases warrant an overhaul of the instrument.

The following normals should be kept in mind regarding comparisons of aneroid barometers:

(a) The temperature correction should be smaller than ± 0.13 hPa per degree Celsius for the station aneroid barometer and smaller than ± 0.26 hPa per degree Celsius for the aneroid altimeter;

(b) The difference between the absolute, corrected read-outs of the tested instrument and those of the test barometer should be smaller than ± 1.3 hPa.

17.6.2.3 Barographs

The testing and comparison of aneroid barographs is carried out according to the following programme:

The barograph is examined thoroughly as follows: condition and accuracy of operation of the clockwork; operation of the mechanical amplifier (leverage) system; operation of the recording system (pen, gate mechanism of the pen arm); play between driving pinion and base-wheel of the drum; condition of the frame and box of the instrument, etc. The results of the examination are entered on the statistical form.

The temperature correction of the instrument is determined for the temperature intervals: $0^{\circ} - 5^{\circ}C$ and $25^{\circ} - 30^{\circ}C$. The procedures for estimating the temperature correction are outlined in the programme for testing aneroid barometers.

Estimation of the instrument's scale correction is made under the controlled conditions of the test chamber. It should be kept in mind that the friction between the pen and recording drum greatly affects the response time of the barograph. At least 20 minutes will be necessary for the barograph to record any change of pressure.

Tests are carried out by decreasing, as well as by increasing pressures and the due time is given for the instrument to indicate each new pressure value.

A large scatter of corrections in value and sign warrants adjustment of leverage and recording mechanism. The comparison should be repeated.

The following normals should be kept in mind regarding the testing of barographs:

(a) Play of the drum causing a time-axis origin shift should be smaller than 1/3 time-scale division;

(b) Jumps of the pen (due to excess friction between pen and paper) should be kept within the limits imposed by the safe recording and accuracy requirements. Maximum jumps should be smaller than 1.03 hPa;

(c) Temperature correction should be smaller than 0.17 hPa per degree Celsius;

(d) Corrections at the two scale extremes should be smaller than 1.5 scale division for a zero correction in the middle of the scale.

17.6.2.4 Hypsometers

The testing of hypsometers (surface) is carried out according to the following programme:

The hypsometer is examined for the state of the alcohol burner and thermometer. The design of the field hypsometer ensures that no water droplets can enter the thermometer reservoir space when the hypsometric liquid boils. The examination of the thermometer is aimed at finding faults like mercury deposits along the capillary, moving scale, etc., which may ruin the accuracy of the method.

Hypsometer thermometers having $0^{\circ}C$ division on the scale are first tested for the accuracy of their zero and for the zero depression by heating. The zero depression is tested by heating the thermometer up to the boiling point of the water in the boiling kettle and then again subjecting it to control of the $0^{\circ}C$. Hypsometer thermometers are read-out to the nearest 0.001° using a magnifying glass.

Temperature readings are taken at the ambient pressure of the laboratory (to an accuracy of 0.13 hPa) every five minutes and the averaged observation data are used in the formula:

$$P = 760 + \frac{t_{boil} - 100^{\circ}}{0.0375}$$

The results of the comparison between the hypsometer and the test barometer are plotted on a graph. It is desirable to check the instrument at different atmospheric pressures.

Hypsometer thermometers may be tested in a special boiling kettle, inside which the pressure can be varied. The pressure inside the boiling kettle is measured by the test barometer, whose cistern is connected to the boiling-water space through a hose and a water-vapour trap.

The following normals should be considered regarding the comparison of a hypsometer:

(a) The $0^{\circ}C$ depression after the hypsometer's thermometer has boiled for half an hour should not exceed $0.1^{\circ}C$;

(b) The pressure-correction change for every 10 mm Hg should not exceed 0.3 mm Hg.

17.6.3 Mercury-purification and barometer-filling station

A repair to a mercury barometer often means refilling the barometer's tube or a complete change thereof. The need to refill may stem from a deterioration in the qualities of the mercury or a degradation of the Torricellian vacuum. Whatever the reason, the mercury to be used for the purpose must be pure and the mercury-purification process comes into the question when used mercury has to be resorted to for the purpose of barometry.

17.6.3.1 Mercury purification

The mercury-purification procedures may be carried out in the conditions of the mercury laboratory with simple technical means in the following seven steps:

(a) Mechanical filtering;

(b) Washing in a solution of HNO_3 ;

(c) Washing in distilled water;

(d) Mechanical filtration;

(e) Washing in NaOH, $Hg_2(NO_3)_2$;

(f) Washing in distilled water;

(g) Distillation.

Although simple in principle, the mercury purification is a lengthy procedure needing experience and extra care. Some of the mercury-purification agents are corrosive and need to be handled with caution.

(a) Mechanical purification

Mechanical purification consists of filtering the mercury and is aimed at removing all solid substances that might be admixed with it; dirt, oxides, unsoluble metal particles, etc.

The filtering qualities of mercury are not as good as those of ordinary liquids, which is why filtering through "large-hole" filters is applied and multiple filtering is recommended. One simple mercury-filtering apparatus (shown in Figure 208) consists of a glass funnel with a filter paper cone lining, which is impenetrable by the mercury and is therefore perforated (between 30 and 50 holes) near the apex of the cone using a thin (0.3 - 1 mm) needle.

The mercury poured into the funnel drips out slowly into a clean flask half-filled with water. In the process of filtering, precipitation of the larger foreign particles takes place onto the paper cone surface and, at the end of the filtering of the portion of mercury, it appears rather dirty.

The use of a new paper cone is recommended for each new portion of mercury;

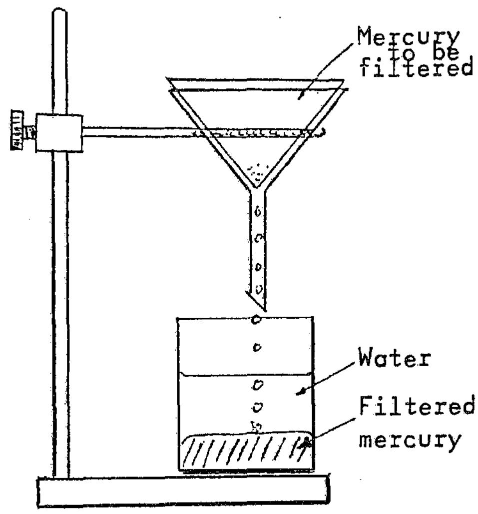


Figure 208 - Mechanical filtering of mercury

(b) Washing in a nitric-acid solution

The washing liquid consists of a 1:1 ratio of nitric acid (HNO_3, 1.4 density) and distilled water and the washing procedure is illustrated in Figure 209. The mercury is placed in an open flask (one-third of its volume taken) and the nitric-acid solution is poured on top (about 20 mm deep).

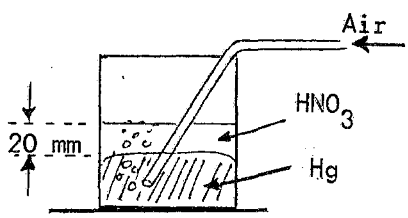


Figure 209 - Washing procedure with nitric acid

Air from a pump is bubbled through the mercury using a bent glass tube. The bubbles bring all the mercury into contact with the nitric acid, thus helping in the solution of all metals and other foreign matter in the HNO_3 layer, which is disposed of afterwards.

The HNO_3 washing procedure takes six hours per portion of mercury;

(c) Washing of mercury in water

Water-washing of the mercury processed by nitric acid takes from about six to ten hours and is aimed at removing all traces of nitric acid from the mercury. The washing procedure needs the combined action of the flowing water and the air-bubbling mechanism. The simple apparatus used for this purpose is pictured in Figure 210.

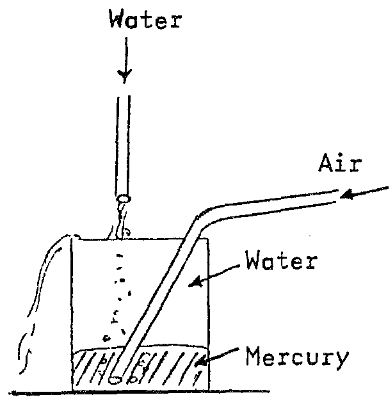


Figure 210 - Water-washing of mercury

The only difference between the set-up in Figures 209 and 210 is that, with water-washing, the dirty water overflows the flask, which must therefore be placed in the sink.

The water-washed mercury is then subjected to further purification procedures;

(d) Second mechanical filtration

The second mechanical filtration is carried out with the help of the simple paper-cone filtering device already discussed (Figure 208). For the second filtration, the paper-cone filter should have a single perforation of about one millimetre in diameter at the apex of the cone.

The purpose of the second filtration is to take away those solid particles which may have escaped solution in the nitric acid;

(e) Washing in potassium hydroxide (NaOH) and 15%, 10%, 5% solutions of mercurous nitrate ($Hg_2(NO_3)_2$)

Four washing stages like the one pictured in Figure 211 are necessary for this purification procedure.

At the first stage, the receiving flask is filled with NaOH solution (300 g NaOH + 1 000 g of H_2O), which removes any fats which may have contaminated the mercury.

The second stage uses a 15% solution of $Hg_2(NO_3)_2$; the third stage a 10% solution and the fourth stage a 5% solution of the same mercurous salt. $Hg_2(NO_3)_2$ has a strong reducing action and removes oxide contaminants.

At each stage, the dripping device is filled with the mercury collected in the clean flask of the previous stage.

It is advisable to place all the washing devices in a row and to follow strictly the sequence of operations outlined above;

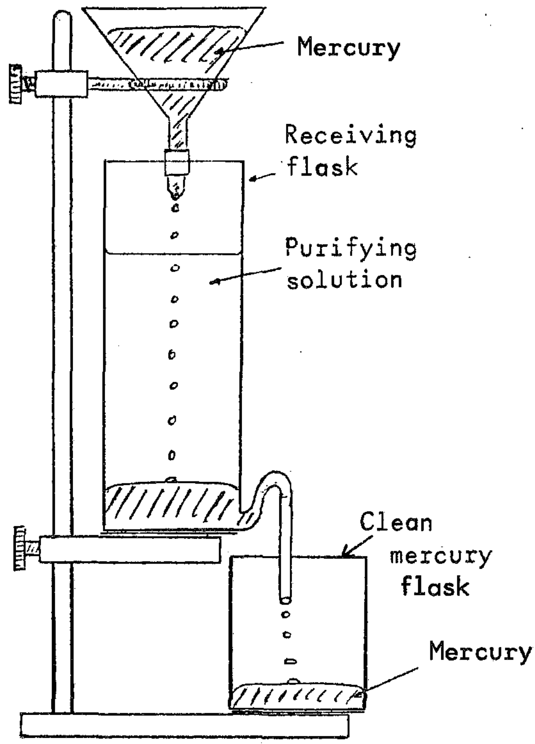


Figure 211 - Device for NaOH and $Hg_2(NO_3)_2$ washing

(f) Second water-washing

The last-stage $Hg_2(NO_3)_2$ solution mercury output is double-washed in water using the method outlined in (c) above. The clean mercury is collected in a clean flask ready for the last stage of purification - the distillation.

Before the discussion of distillation procedures and devices, let us briefly consider the matter of the solutions of purifying agents used thus far.

The necessary concentration of NaOH solution is obtained from 300 g granulated NaOH and 1 000 g (or cm^3) of distilled water.

Mercurous nitrate ($Hg_2(NO_3)_2$) is obtained by mixing 20 cm^3 of mercury and 130 cm^3 of concentrated nitric acid. The reaction takes 30 to 40 minutes to complete. The resulting substance should be left to cool to room temperature and be filtered before its dilution with distilled water, according to the following proportions:

- 15% solution: 17.65 g $Hg_2(NO_3)_2$ + 100 ml H_2O;
- 10% solution: 11.11 g $Hg_2(NO_3)_2$ + 100 ml H_2O;
- 5% solution: 5.26 g $Hg_2(NO_3)_2$ + 100 ml H_2O;

The process of mercury purification may be semi-automated using a battery of washing devices, the washed mercury of each one being transferred to the next with the use of a vacuum pump.

(g) Mercury distillation

Distillation is the last stage of the mercury purification procedure, distilled mercury being the grade of purity necessary for barometric purposes.

The mercury distillator presented schematically in Figure 212 is made of special heat-resistant glass. Its design includes the following specifications:

- Inlet tube (1) inserted in the mercury to be distilled in a glass container (8), whose position in relation to the inlet tube, along the vertical, is regulated periodically with the help of the adjusting screw (7), so that the level of the mercury in the evaporation vessel is kept nearly constant;

- Heater (2) - ring-shaped electrical heater having an adjustable power output;

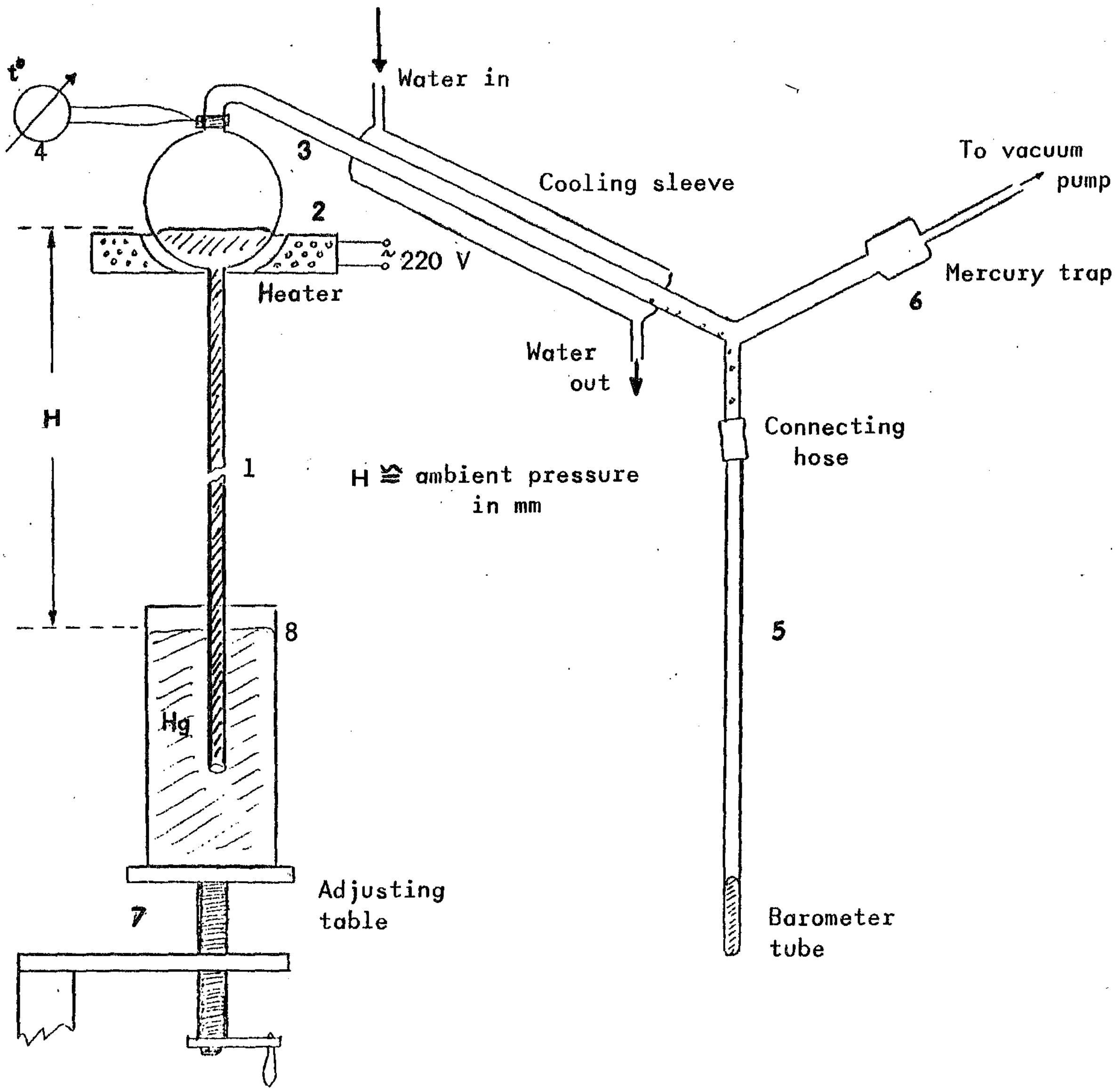


Figure 212 - Mercury distillator

- Mercury-evaporation vessel (3), ball-shaped, made of heat-resistant glass (boiling point of mercury = 357°C);

- Thermocouple thermometer (4), monitoring the mercury-evaporation temperature, which should be kept just below the boiling point of mercury in order to prevent mercury droplets "splashing out" into the "clean" portion of the distillator;

- The signal from the thermocouple thermometer can be used in the automatic regulation of the evaporation temperature produced by the heater;

- Part of the distillator outlet tube is cooled continuously by running water circulating in the cooling sleeve. The condensed mercury in the form of small droplets finds its way gravitationally along the sloping outlet tube and into the attached barometer tube (5). (Instead of a barometer tube, a collecting vessel may be attached to the connecting hose of the outlet);

- The mercury-vapour trap (6) is a cool chamber to trap any mercury vapours which have escaped condensation. Mercury droplets are prevented from entering the vacuum pump, which is working continuously throughout the distillation process, in order to keep the level of mercury in the evaporation vessel constant.

The feed vessel (8) is filled with thoroughly-washed mercury and placed on the adjustable-height table under the inlet tube (1). The crank-handle of the adjusting screw is actuated and the inlet tube is dipped into the mercury to a depth of about two-thirds of the vessel's height. A thoroughly-cleaned and dried barometer tube is connected to the outlet tube of the distillator.

The vacuum pump is switched on, bringing the mercury to be distilled into the evaporation space of the evaporation vessel. With the help of the adjusting screw, the level of the mercury in the evaporation vessel is brought to one-third of the height of the vessel.

The barometer tube to be filled with mercury is degassed under vacuum by heating with an electric heater or a blow-torch, starting from the bottom of the tube.

When the degassing procedure is finished, the evaporation heater is switched on to full power and the cooling water starts to circulate. The temperature increase is observed, as well as the mercury level inside the evaporation vessel.

When the temperature in the evaporation vessel reaches 300°C, the power of the heater starts to be regulated so as to keep the temperature of the mercury below its boiling point.

The level of mercury in the evaporation vessel is watched and readjusted periodically as is the evaporation temperature, which may vary because of mains voltage fluctuations.

Prolonged exposure to an atmosphere polluted by mercury vapours should be avoided. Mercury should be handled with great care. It should be borne in mind that gold and silver are easily dissolved in mercury and the operators should therefore leave any jewelry outside the premises.

17.6.3.2 The mercury-barometer filling station

The mercury-barometer filling station is part of the mercury laboratory, both territorially and functionally.

The premises of the mercury laboratory and the barometer-filling station should be accessible only from the outside of the building accommodating them. Special precautions should be taken for the ventilation of the premises and for their regular cleaning.

Facilities should be provided in the laboratory for the complete maintenance of the mercury barometers.

A guide to the equipment layout and furniture of a mercury laboratory is presented in Figure 213.

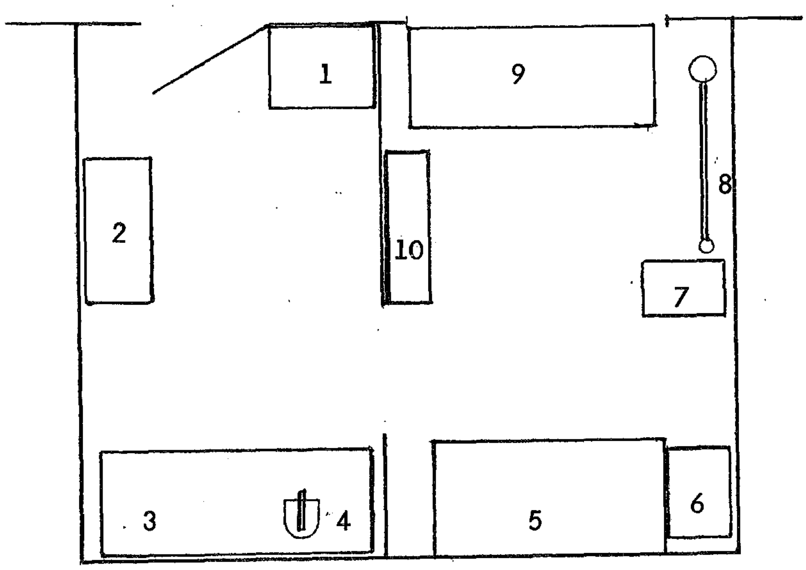


Figure 213 - Mercury laboratory and barometer-filling station

The main items or equipment and furniture given in the figure are as follows:

(1) overalls, gloves cabinet;

(2) glassware, materials cabinet;

(3) barometer-disassembly station;

(4) gas or gasoline burner (glass work);

(5) mercury-purification (washing) station;

(6) water top and sink;

(7) vacuum pump (outlet outside the laboratory space);

(8) barometer-filling station and mercury distillator;

(9) barometer assembly station;

(10) barometer-tube rack.

A few hand-tools of special design are necessary in the mercury laboratory besides the ordinary handtools:

- Set of screwdrivers;
- Set of pliers, tweezers, scissors, knife;
- Set of wrenches and Allen keys;
- Set of horse-shoe wrenches (cistern dismantling);
- Hand-vice and adjustable clamps, set of washer punches (3 to 15 mm);
- Alcohol burner, electric-tube heater, electric-tube cutter.

The necessary materials, chemicals and glassware are as follows:

(a) Materials

- Pressure hoses, various diameters and types;
- Sheet of insulation material (suitable for washers);
- Sealing wax;
- Sulphur powder (for cleaning mercury spillages);
- Vacuum resin;
- Grease;

(b) Chemicals

- Nitric acid;
- Potassium hydroxide;
- Mercurous nitrate;

(c) Glassware

- Jena-glass pots, various sizes;
- Glass flasks, various capacities;
- Funnels, ordinary and fritted;
- Glass tubes, 6 mm, 9 mm, 12 mm, 15 mm;

17.6.3.3 Preparation of barometer tubes for filling with mercury

Barometer tubes are prepared from stock glass-tubes through the application of a few operations:

- Selecting the glass-tube bore and type;
- Cutting the glass-tube to size with an allowance for sealing the upper end and rounding the lower end (or rather forming it);
- Sealing of the end of the glass tube using the gas (gasoline) burner;
- Washing the barometer tube inside using NaOH solution, water, HNO_3 and again water; drying;
- Attaching the threaded nipple to the barometer tube (depends on the specific instrument's design) using a heat-resistant synthetic resin;
- Degassing the tube under vacuum with application of heat;
- Filling the tube with mercury under vacuum.

17.7 Temperature/humidity laboratory

The meteorological control of the meteorological surface network temperature and humidity measuring instruments lies with the temperature/humidity laboratory (T/HL). The following groups of instruments are involved in its major testing, control and calibration activities:

- Liquid-in-glass thermometers;
- Bimetallic and liquid-in-steel thermographs;
- Electrical resistance thermometers;
- Psychrometers;
- Organic sensor hydrometers and hydrographs;
- Electrolytic hygrometers.

The calibration stability of these difference groups of instruments varies over a wide range. The frequency of periodic checks and calibration of some of them is indicated on page 252.

The standard instruments used in the testing and calibration of temperature- and humidity-measuring instruments are the standard thermometer and the standard psychrometer.

The standard thermometers are a set of wetting- and non-wetting-liquid thermometers covering the range of meteorological temperatures and certified as standard instruments.

Auxiliary calibrating instruments are used as well:

- Thermometers for control of the 0°C, having a scale division of 0.02°C;
- Thermometers for the control of the boiling point of water, having a scale division of 0.02°C;
- Platinum resistance thermometers and related resistance meters

(accuracy compatible with 5×10^{-5} relative measurement error). High-accuracy voltmeters;

Mercury barometer of 0.1 hPa accuracy.

The standard psychrometer is an instrument using tested and certified thermometers and a controlled-ventilation air speed.

The test and calibration equipment used in the laboratory is as follows:

- Thermometer-testing bath, partial thermometer immersion;
- Thermometer-testing bath, total thermometer immersion;
- Thermograph-testing cabinet;
- Thermo-hygrochamber;
- Hygrograph-testing hygrostat (a duplication of the thermo-hygrochamber);
- Dewar vessel having a bottom water-outlet;
- Boiling-point-of-water thermostat (not obligatory).

The temperature constancy of the thermostats used in the thermometer calibration procedures should be compatible with the maximum acceptable calibration error for the thermometer under test, as reflected in the following table:

Maximum acceptable calibration error in °C (random)

Measuring range of the thermometer	Smallest scale division (°C)				
	0.05	0.1	0.2	0.5	1.0
	Non-wetting thermometric liquid (mercury)				
- 55°C to - 5°C	0.05	0.1	0.2	0.2	0.5
- 5°C to + 60°C	0.02	0.05	0.1	0.2	0.5
+ 60°C to + 105°C	0.05	0.05	0.1	0.2	0.5
	Wetting liquid (pentane ethyl alcohol, toluol)				
- 200°C to - 55°C	-	-	-	0.5	0.5
- 55°C to - 5°C	-	-	0.2	0.2	0.5
- 5°C to + 60°C	-	-	0.2	0.2	0.2

A brief description of the various temperature- and humidity-calibration equipment types follows:

The thermometer-testing thermostat, partial thermometer immersion, is shown schematically in Figure 214. This is the simplest thermometer-calibration thermostat. It consists of two major parts: thermostatic chamber (Figure 214) and cooling plant (Figure 215).

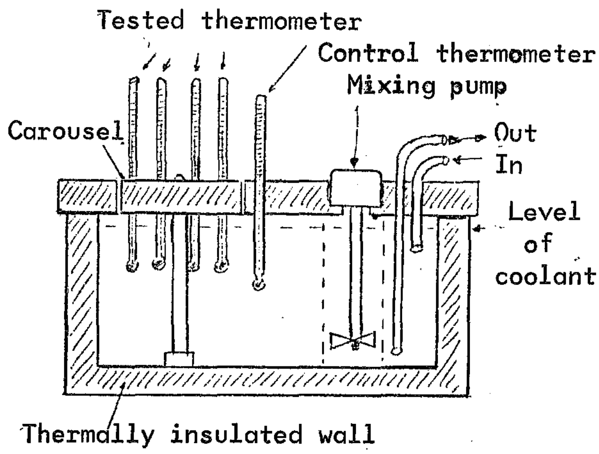


Figure 214 - Principle of the thermometer thermostat, partial immersion

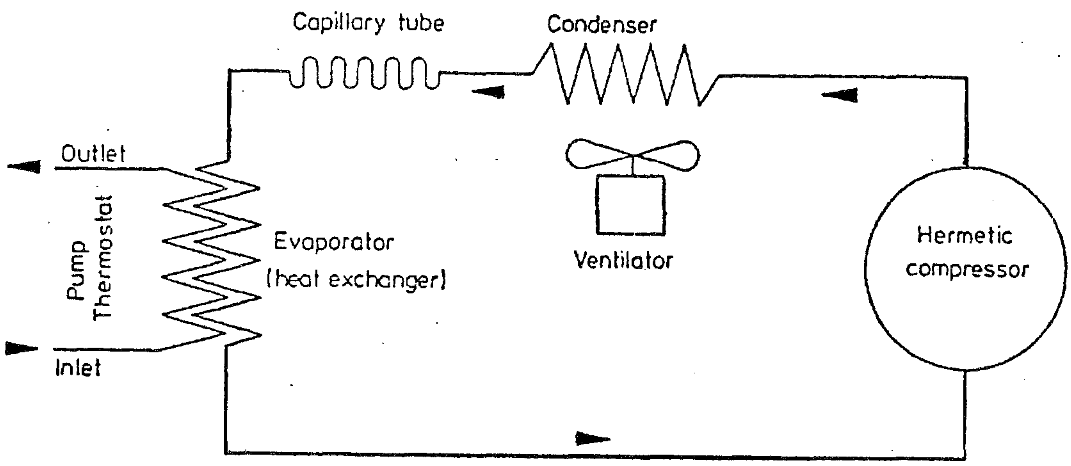


Figure 215 - The cooling plant - schematic diagram

The cooling plant cools down the cooling agent (usually alcohol), which is circulated by a pump through the test chamber. An additional mixing pump ensures the thorough mixing of the cooling agent and the establishment of a homogeneous temperature field inside the thermostat.

The tested thermometers have their reservoirs immersed in the cooling liquid by being securely fastened to a manually-operated carousel stand.

The thermometer test procedure is as follows:

(a) The thermometers under test are compared, one by one, with the control thermometer, starting with the 0°C temperature of the cooling agent (later going up or down, depending on scale range), by turning the carousel in order to bring each tested thermometer close to the control thermometer and leaving it this way for a time span at least seven times the lag-coefficient of the tested thermometer (it is assumed that the control thermometer has a smaller lag-coefficient, the temperature step = 10°C).

The mixing pump is left working until about one minute prior to the reading of the thermometers. The read-outs are entered on the test form.

No correction for the temperature of the stem of the tested thermometer (the part which is outside the cooling liquid) is applied if the temperature difference cooling agent/thermometer stem is less than 10°C. The temperature of the thermometer stem is measured by a special long-reservoir thermometer attached to it (or else is assumed to be the room temperature). An average temperature is calculated for this stem;

(b) The cooling plant is left running (the mixing pump as well) until the next temperature testing-point is reached, which is selected based on the table below.

Each tested thermometer is brought near the control thermometer and left there long enough to assume the test-point temperature.

One minute prior to taking the comparison reading, the mixing pump is stopped (the temperature drift (degrees per minute) of the chamber, with mixing and circulation pumps standing still, should be much less than the value of the smallest scale division of the tested thermometer).

Thermometer test point

Smallest scale division	Test point
0.01°C	Every 1°C
0.02°C	Every 2°C
0.05°C	Every 5°C
0.1 °C	Every 10°C
0.2 °C	Every 20°C
0.5 °C	Every 50°C

The read-out is corrected for the thermometer's stem temperature using the following formula:

$$t^{o} = t_{test} + k_{f}$$

where k_f = stem-temperature correction.

$$k_{f} = n.g(t^{o}_{th} - t^{o}_{f})$$

where:

n = length of the thermometer stem in °C (the part above the coolant);

g = coefficient of relative thermal expansion of the thermometric liquid in the specific thermometric glass (see table below);

t_{th} = the thermometer read-out;

t_f = mean temperature of the thermometer stem;

<u>Values of the relative coefficient of thermal expansion, g</u>

Temperature range	Kind of thermometric glass			
	16'''	2954'''	Super-max	Quartz
	Mercury and mercury-thalium			
- 50°C	0.000157	0.000163	0.000171	0.000181
0°C	0.000158	0.000164	0.000172	0.000181
+ 50°C	0.000158	0.000164	0.000172	0.000181
	Pentane	Ethyl alcohol	Toluol	
- 100°C	0.0010	-	-	
- 80°C	0.0010	0.0009	0.0010	
- 60°C	0.0011	0.0009	0.0010	
- 40°C	0.0012	0.0010	0.0010	
- 20°C	0.0013	0.0010	0.0010	
0°C	0.0014	0.0010	0.0010	
+ 20°C	0.0015	0.0011	0.0010	

(c) Each test-point temperature correction should be the average of at least five read-outs.

Note: Generally, the routine test procedures are started with the 0°C test point, using the Dewar flask and a melting ice charge.

The remaining test points are obtained, using the thermostat:

(i) For thermometers having a negative temperature scale only - downward from 0°C;

(ii) For thermometers having a positive temperature scale only - upward from the 0°C scale division;

(iii) For thermometers having both positive and negative temperature scales - first from 0°C downwards, then from 0°C upwards;

(d) For test points in the direction of increasing test-chamber temperatures, an electric heater is used in place of the cooling plant.

The thermometer-testing thermostat with complete immersion (Figure 216) makes the testing procedures easier, because no thermometer-stem correction is applied.

A similar test procedure is used with the complete immersion unit as with the previously discussed unit. The only difference is the dropping of the stem correction.

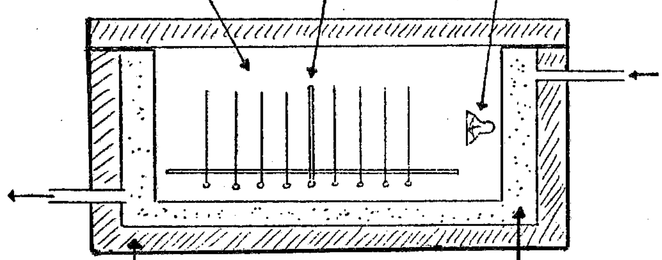
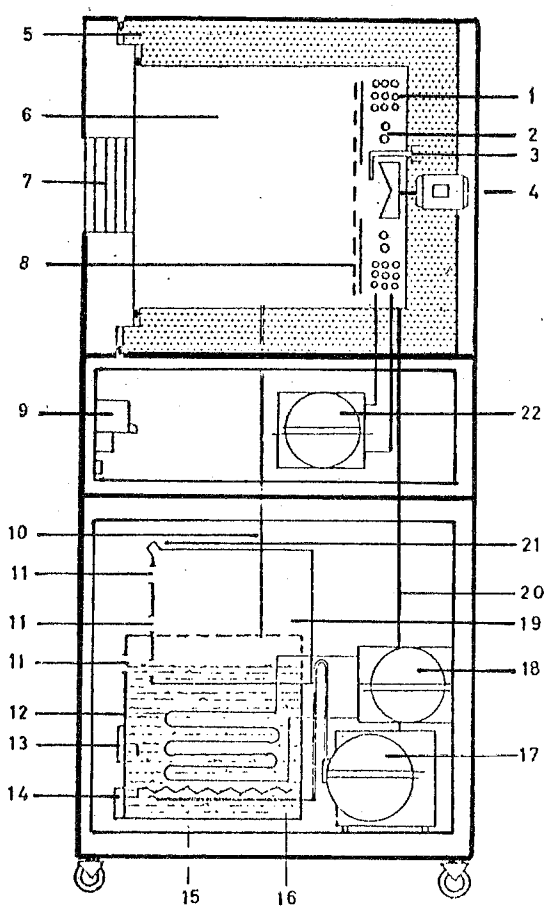


Figure 216 - "Complete immersion" thermometer thermostat



(1) cooling coil (chamber)
(2) heating (chamber)
(3) temperature feeler PT 100 (chamber)
(4) fan (chamber)
(5) insulation
(6) chamber
(7) window
(8) baffle
(9) temperature and humidity control
(10) duct for the temperature-controlled air
(11) spy-glasses for checking the water level
(12) cooling coil (humidifying and dehumidifying unit)
(13) temperature feeler PT 100 (humidifying and dehumidifying unit)
(14) heating with protection against "no water"
(15) air distributor
(16) humidifying and dehumidifying unit
(17) air compressor
(18) cold plant for the humidifying and dehumidifying unit
(19) storage container for distilled water
(20) suction pipe (air compressor)
(21) feed pipe for purified water
(22) cold plant (chamber)

Figure 217 - Cross-section view of a thermo-hygro chamber

The general appearance of a thermograph-testing cabinet (temperature range: - 20°C to + 50°C; power rating: 1.2 kW) is shown in Figure 218.

A contact thermometer is used as a thermometric sensor for the cooling plant and a separate comparison thermometer is provided for calibration purposes.

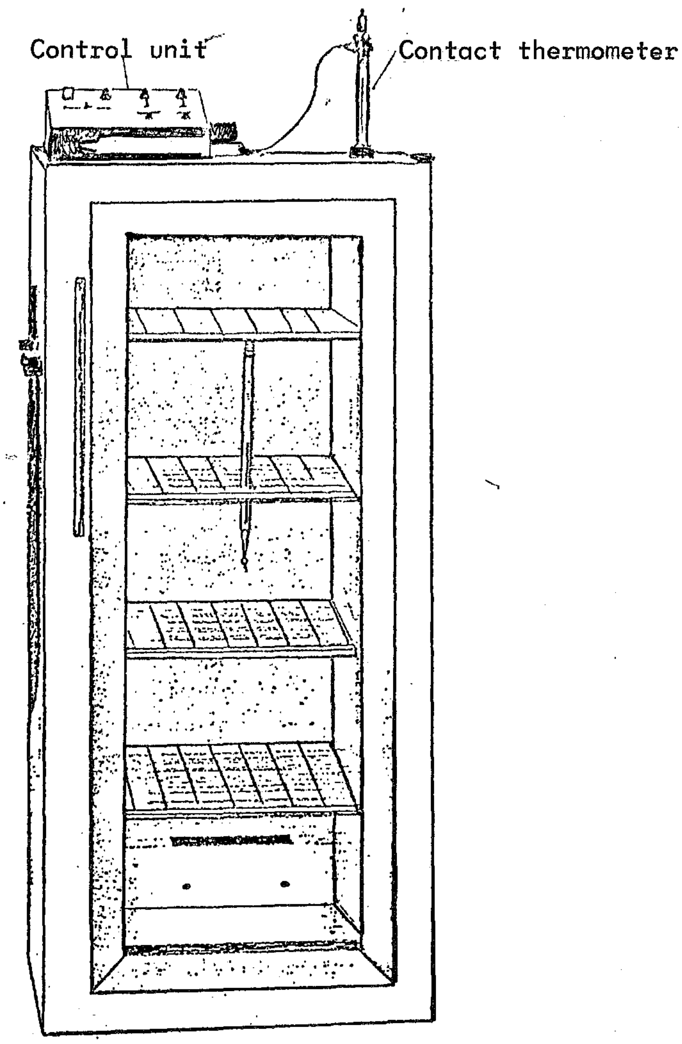


Figure 218 - Thermograph-testing chamber

A cooling plant, like the one shown in Figure 215, is used with the thermograph-testing cabinet. An inferior constant temperature is attained with such equipment (no higher than 0.2°C) because of the larger dimensions of the chamber.

A combined thermo-hygrochamber's cross-section view and operating principle are illustrated in Figure 217.

The test-chamber air temperature is controlled through the cooling coil connected to the cooling plant of the unit. The cooling plant itself is controlled by a platinum resistance temperature sensor and the controlling electronic circuitry.

The test-chamber air is re-circulated through the thermally controlled humidifying/de-humidifying unit, the process being controlled by an automatic humidistat using a Pt_{100} psychrometer.

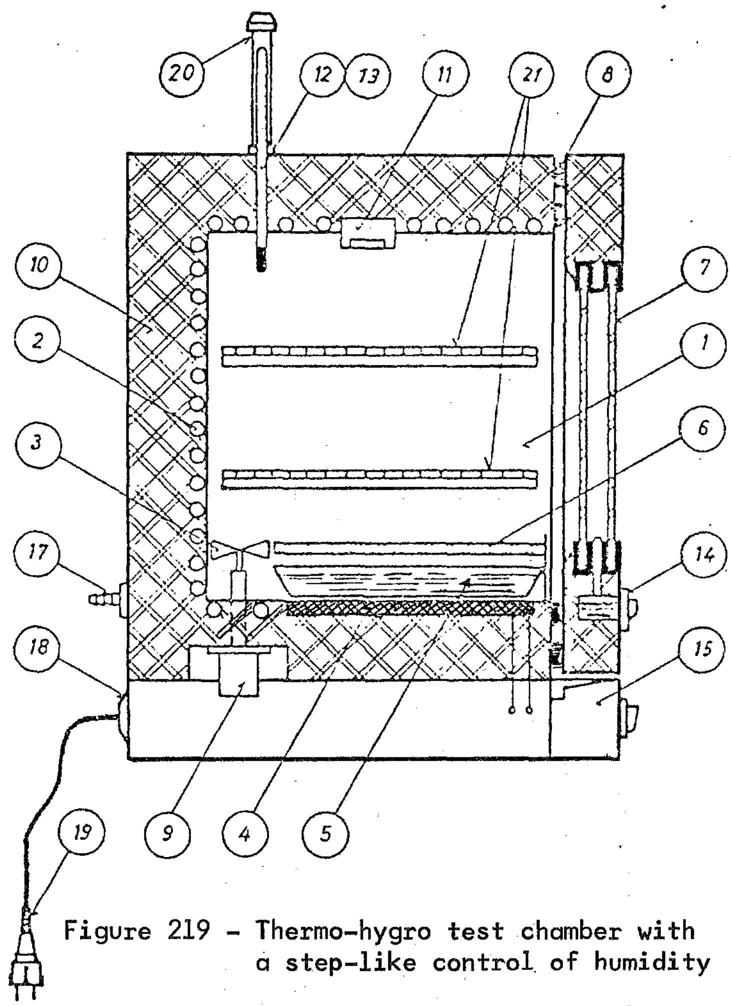


Figure 219 - Thermo-hygro test chamber with a step-like control of humidity

The different parts of the testing chamber (Figure 219) are numbered as follows:

(1) test space;
(2) piping of the coolant coil;
(3) chamber ventilator;
(4) three-step power rating electrical heater;
(5) plastic (glass) basin with the humidifying solution;
(6) glass shield;
(7) door window;
(8) rubber cushion;
(9) ventilator motor;
(10) wall insulation;
(11) space lighting;
(12) dry-bulb thermometer;
(13) wet-bulb thermometer;
(14) silica-gel container;
(15) electronic control unit;
(16) cooling-coil nipples;
(17) power fuses and cord;
(18) power plug;
(19) contact thermometer (adjustable);
(20) instrument shelves.

The dehumidification is attained through the recirculation of the chamber air through a container filled with a desiccant (silica gel). The constant temperature of the equipment is about 0.3°C. The humidity value can be controlled within the limits of + 5%. The cross-section view of a simpler chamber of this kind is shown in Figure 219.

A fixed-point humidifier is the basin (5) filled with a humidifying solution. The solution can be changed for a step change of the humidity inside the test space.

A cooling plant circulates a coolant through the coil (2), the temperature being controlled by an adjustable contact thermometer.

A typical output curve for an average thermo-test chamber is shown in Figure 220. The power rating of the cooling plant is about 1.8 kW. The test space is about 70 litres.

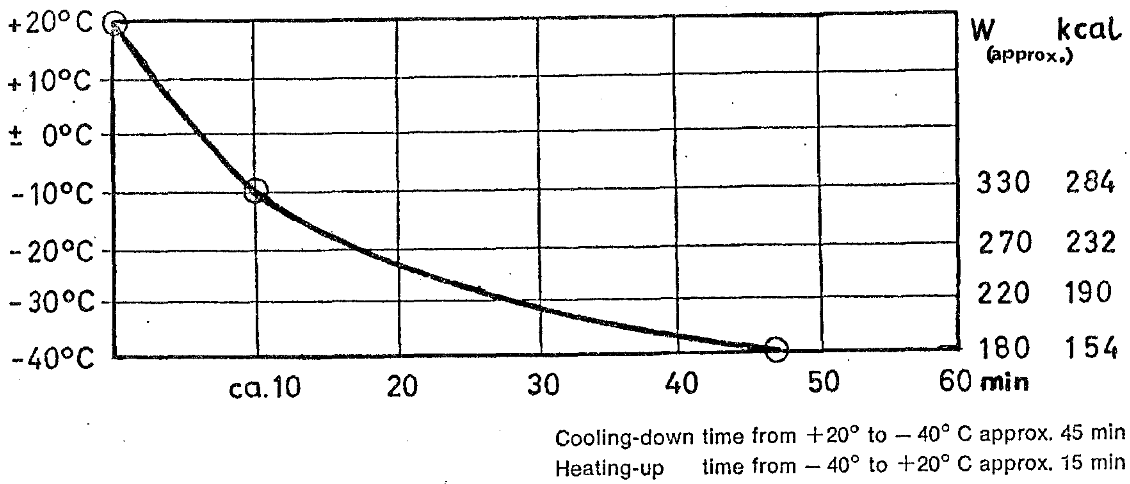


Figure 220 - Average thermo-chamber output curves (70-litre test space)

The working range of the humidifier/dehumidifier unit of a hygro-test chamber is shown in Figure 221. It illustrates how the drying unit expands the humidity/temperature range of the test chamber by absorbing part of the water vapour contained in the air volume of the test space, initially equal to the water vapour contained in the ambient air.

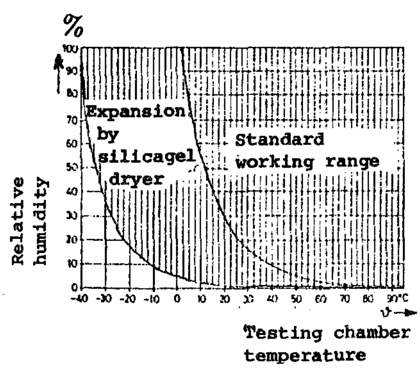


Figure 221 - Output curves of humidifier

Silica-gel drying units need regeneration after a few drying cycles. Regeneration is obtained by heating the drying gel to a temperature of 120 °C.

17.7.1 Summary of the desirable features of thermostats and test chambers

(a) Homogeneous field of temperature (humidity, for humidity test chambers), with no vertical or horizontal gradients of the measured variables;

(b) Facilities for continuous change of the measured variable in both increasing and decreasing directions at a predetermined speed;

(c) Adequate provision for accurate measurements of the measured variable, preferably with recording;

(d) Adequate provision for a good visual observation of the instruments under test;

(e) Convenient operation of and repeatable results from the equipment.

17.7.2 Standard instruments

Working standard thermometers are of the psychrometric type, certified, based on comparison with higher-class standards (platinum resistance standard thermometer).

The working standard thermometer's correction at 0°C should be 0.00°C. A smaller, established 0°C error change with time warrants a new comparison of the working standard with a higher-class instrument.

Mercury working-standard thermometers are used in the calibration of mercury thermometers and wetting-liquid standard thermometers are used in the calibration of wetting-liquid thermometers.

Standard thermometers are stored as far as possible at a constant room temperature, the wetting-liquid type being stored in a vertical position. The spread of 0°C corrections of standard thermometers should not lie outside the range $\pm$ 0.05°C, but the requirement for wetting-liquid thermometers is less stringent.

The standard (working) psychrometer uses certified thermometers. An electric motor-driven aspirator is preferable for the standard psychrometer. The turning speed of the ventilator should be stabilized against mains fluctuations and should provide a ventilation speed which is known and remains at all times within the limits 2 - 2.4 m s^{-1}.

The psychrometer's aspirator ventilation speed is checked, using microprobes (similar to Pitot tubes) and a Krell micromanometer.

All temperature and humidity working standards are checked for change in corrections at two-month intervals.

17.7.3 Routines

Test and calibration of the various thermometers used in the meteorological network are preceded by a physical examination of the thermometers.

The general examination is aimed at revealing defects or sources of measurement errors of a general character:

- Good condition of capillary, scale and scale divisions, reservoir;
- Absence of moisture inside the glass sheath of the thermometer;
- Unbroken thermometric liquid column;
- Absence of thermometric liquid stains or residues inside the capillary;

- Absence of bubbles in the thermometric liquid column.

The specific examination of the thermometers concerns their proper operation for the purpose for which they are designed:

- Maximum thermometers' preservation of maximum-temperature indication abilities;

- Minimum thermometers' preservation of minimum-temperature indication abilities.

The calibration of the thermometers starts with a check of their $0^{\circ}C$ indication. The verification of the $0^{\circ}C$ indication of the thermometer is best done with the help of the Dewar vessel filled with melting ice. Attention should be paid to the purity of the water from which the ice has been obtained (157 mg of salt in one litre of water causes a temperature depression of the melting ice temperature of nearly $0.01^{\circ}C$).

The thermometer's stem is also subjected to the cooling effect of the melting ice coolant, at least slightly above the $0^{\circ}C$ scale division.

Maximum thermometers are cooled below $0^{\circ}C$ before the test of their $0^{\circ}C$ scale division correction.

The time of adaptation of the thermometer to the test temperature may be calculated from the formula:

$$T = \lambda \times 2.3 \log\left(\frac{t_o - t_t}{t - t_t}\right) \quad (s)$$

where:

λ = lag coefficient of the thermometer;

t_o = initial temperature read-out of the thermometer;

t_t = test point temperature, $t_o - t_t$ is the temperature "step";

t = thermometer temperature read-out after time T in seconds; $t - t_t$ is the actual accuracy of the temperature measurement after T of temperature adaptation of the thermometer.

A simple calculation shows that with a temperature step of $10^{\circ}C$ and a tolerable measurement accuracy of $0.01^{\circ}C$, the adaptation time will be seven times the actual lag-coefficient of the thermometer.

As already pointed out, the calibration routines are based on multiple measurements and averaging of the measurement results over at least five measurements for each test point (at least ten measurements for comparisons between standard instruments). Calibration of the thermometers at positive temperatures is carried out at selected test points (temperature step of $5^{\circ}C$ or $10^{\circ}C$ or larger, depending on the scale division of the tested thermometer). Comparison read-outs are started about $0.2^{\circ}C$ before reaching the test point and stopped about $0.2^{\circ}C$ after it.

Test-thermometer corrections are taken into account and a correction for the thermometer-stem temperature is applied, if necessary.

The calibration of the thermometers at negative temperatures is carried out in the same way as for positive temperatures. The first test point may be $-5^{\circ}C$ or $-10^{\circ}C$ depending on the selected temperature step, decreasing to the lowest temperature of the tested thermometer.

The requirements concerning maximum scatter of the differences in the read-outs of tested and control thermometers are different for the different categories of thermometers. Generally, scatter reaching $\pm$ 0.5°C should be viewed with suspicion and the test should be repeated.

Differences in the read-outs of tested and control thermometers, as far as aspirated psychrometer's thermometers are concerned, should not exceed 0.15°C for one test point.

The thermometer's test certificate should be accompanied by a graph illustrating the scatter of the corrections. The calibration certificate should contain in an explicit form the conclusions concerning the acceptability of the thermometer for its application.

17.7.4 Calibration of thermographs

An external examination is carried out of thermographs awaiting calibration concerning:

- General condition of the instrument's frame, lid, window;
- Condition of the sensor, apprearance of its surface, its shape;
- Condition of the mechanical amplifier leverage, allowable play in the various links, smooth operation;
- Condition of the recording mechanism and pen, friction between pen and recording paper, movement of the pen arm between its extreme positions;
- Condition of the clockwork mechanism, play in the driving gear.

The calibration of thermographs is best carried out in an air medium, such as the ordinary thermo-chamber.

Four test points for temperature are selected: + 40°C, + 20°C, 0°C and - 30°C. Several readings are taken at each test point. The difference between tested thermograph readings and control thermometer readings are averaged. If an error is found concerning the 0°C scale division and the instrument can provide for a slight adjustment of the scale, the correction is made to an accuracy of 0.0°C and the instrument is subjected to a second calibration.

A graphical representation of the scatter of the corrections over the different temperature ranges is made.

The following are thermograph-calibration normals:

- The absolute value of the correction at the scale extremes should not exceed 1°C for a correction at 0°C equal to 0.0°C;
- The difference in corrections for each 10°C temperature interval should not exceed 0.5°C;
- The time-base correction (arising from play in the clockwork gears) should be confined to within a quarter of a time-scale division for the weekly clock and one-third of a scale division for the 24-hour clock;

- The accuracy of the clock rotation should be better than + 30 minutes for the weekly clock and not worse than ± 5 minutes for the daily clock.

17.7.5 Psychrometer testing

Aspirated psychrometers are subjected to a pre-test examination in respect of:

- Condition of the thermometers (according to the requirements concerning all liquid-in-glass thermometers);
- Condition of the fabric of the wet-bulb thermometer;
- Condition of the thermometer radiation shields and air-ducts;
- Condition of the aspirator.

The test procedures concerning the psychrometer thermometers are the same as those for thermometers already described.

The ventilation speed of the aspirator is tested, using two microprobes inserted in the air-ducts of the psychrometer near the thermometer's reservoirs and a Krell micromanometer. The following modified manometric formula is used:

$$V = C \times 0.9\sqrt{\frac{2(n - n_o)k\gamma}{\rho}} \quad (\mathrm{m\ s^{-1}})$$

where:

C	=	experimental coefficient valid for the microprobes;
0.9	=	airstream averaging coefficient;
n_o	=	reading of the micromanometer with the aspirator at standstill;
n	=	reading of the micromanometer with the ventilator working;
k	=	coefficient depending on the micromanometer's tube inclination;
γ	=	relative density of the alcohol used with the manometer;
ρ	=	density of the air.

The aspiration constant A changes more rapidly with variation in ventilation velocity below 2 m s^{-1} (considered the lower threshold of ventilation).

Depending on the size of the psychrometer, the spring-driven ventilator should be capable of ventilating the thermometers during a six- to eight-minute period with an acceptable variation of the ventilation speed ± 0.2 m s^{-1}, but not lower than 2 m s^{-1} in absolute value.

Electric-motor-driven psychrometers should possess a ventilation speed constancy of 10 per cent and an aspiration speed not less than 2 m s^{-1}.

17.7.6 Calibration of hair hygrometers and hygrographs

The hair-hygrometer pre-testing examination consists of:

(a) General examination of the instrument's frame, scale and adjustment screw (zero adjustment and sensitivity adjustment);

(b) Examination of the hair sensor for signs of dirt, forced extension and splits along the hair.

Before the actual testing procedure is started, the hygrometer is kept in a hygrostat (hygro-test chamber) for at least 12 hours at room temperature and 98-100% air humidity. In these conditions, the read-out of the instrument should be within the scale divisions 95 to 100. If this is not the case, a translation of the scale (relative) is effected with the zero adjustment screw in order to obtain the right reading.

The testing is done in the hygro-chamber along a two-leg testing course: descending from 100 per cent and ascending from 30 per cent humidity. The humidity test points are selected at 90, 80, 70, 60, 50, 40 and 30 per cent. Testing of the hair sensor below 30 per cent may cause abnormal behaviour of the sensor at higher humidity values.

Each test-point period should be 15 - 20 minutes long, because of the appreciable lag of the sensor. The humidity-control instrument used in the tests is an electrically aspirated psychrometer.

If, upon return to 100 per cent, the instrument's read-out is found to differ from the right value by a difference observed in the other parts of the scale as well, a new adjustment is made and the test is repeated.

Sensitivity adjustments, if necessary, are made with the help of the screw therefor (changing the leverage relationship), but it should be remembered that, with the irregularity of the hair sensor scale, a number of tests may be necessary before a correct adjustment is obtained. Reaching a $\pm$ 5 % accuracy with this instrument is considered satisfactory.

Goldbeater-skin sensors (animal organic membrane) are subjected to the same test procedure outlined above. These sensors have a smaller lag and a higher signal power than those of hair.

The same test procedure is valid for the hair hygrographs as well. In view of the larger number of hairs in the hygrograph sensor (up to 40) and the subsequently larger lag-coefficient (the time allotted to the single measurement at a test point is longer, i.e. about 30 minutes).

The pre-test examination of the hygrograph includes the following points:

- Examination of frame, lid and window of the instrument;
- Examination of the hair bundle for dirt, split or broken hair;
- Examination of the linearizing mechanism (if present);
- Examination of the recording and arresting mechanisms;
- Examination of the clockwork mechanism.

Accuracy requirements are two per cent at the 100 per cent end of the scale and six per cent in the remaining sectors.

17.8 Anemometry laboratory

Testing and calibration of the following wind-measuring instruments are carried out in the anemometry laboratory (AL):

(a) Heavy-plate (Wild) anemometer: this is a robust instrument used in the measurement of wind speed and direction for operational purposes. Its main advantage is its simplicity of design; the main disadvantages are its inferior accuracy and non-linear response to wind speed;

(b) Rotational-sensor anemometers (anemographs): cup-wheel and propeller-sensor anemometers and recording instruments are widely used in the meteorological network;

(c) Pressure-tube anemometers (anemographs): Pitot- and Prandtle-tube anemometers with sensitive manometers as indicating instruments, are high-accuracy instruments used in the field, as well as in the laboratory;

(d) Thermo-anemometers: based on the principle of convective heat transfer between the sensor and the airstream, these instruments are suitable for the measurement of centimetre-per-second wind velocities;

(e) Anemometers based on other principles (sonic, optical, etc.): these are considered special instruments for use mainly in experimental work.

Two main testing and calibration fields of activities are considered as typical for the anemometry laboratory:

- Routine calibration and testing of field anemometers (anemographs);
- Experimental research testing of wind-measuring instruments.

In relation to other meteorological instruments for operational work, anemometers have a relatively lower frequency of testing, especially those having rotation sensors of modern design.

17.8.1 Calibration equipment

Two kinds of wind-tunnel are used in the calibration routines of the AL:

(a) Open-circuit wind-tunnel (Figure 222);

(b) Closed-circuit wind-tunnel (Figures 223 and 224).

17.8.1.1 Open-circuit wind-tunnel

The open-circuit wind-tunnel (Figure 222) is a test device of simple design, but inferior testing features. Its main components are:

(1) variable speed electric motor;

(2) constant pitch propeller;

(3) windowed test space;

(4) air-inlet cone;

(5) tunnel outlet;

(6) cup-wheel sensor under test.

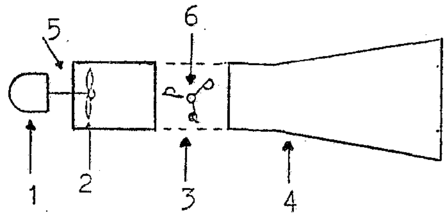


Figure 222 - Open-circuit wind-tunnel

The major shortcomings of this kind of test-tunnel are:

- Noise and draught in the vicinity of the test equipment;
- Narrower range of air speeds and generally lower maximum air speed;
- Greater temperature and turbulence fluctuations in the airstream.

The range of speeds can be improved, within certain limits, by adding an iris-diaphragm and the turbulence of the airstream can be reduced through the use of a honeycomb air-turbulence filter.

For a test-section cross-section of 0.3 x 0.3 m and a maximum air speed of about 30 m s^{-1}, the necessary power will be around 5.5 kW. A d.c. motor can be used, mains/rectifier fed, with independent field and armature speed-control rheostats.

Two alternative designs of the blower are generally used: radial blower and axial blower (propeller fan). The second alternative offers more advantages as far as efficiency and air-speed control are concerned.

Special safety precautions should be taken with open-circuit blowers against injury. Careful balancing of the blower-wheel is necessary against vibrations which may even reach a destructive level by mechanical resonance.

17.8.1.2 Closed-circuit wind-tunnel

Two alternative designs of the closed-circuit wind-tunnel are widely used:

(a) Wind-tunnel duct in a vertical-plane version (Figure 223);

(b) Wind-tunnel duct in a horizontal-plane version (Figure 224).

One or the other design may be preferred, according to space considerations at the installation site.

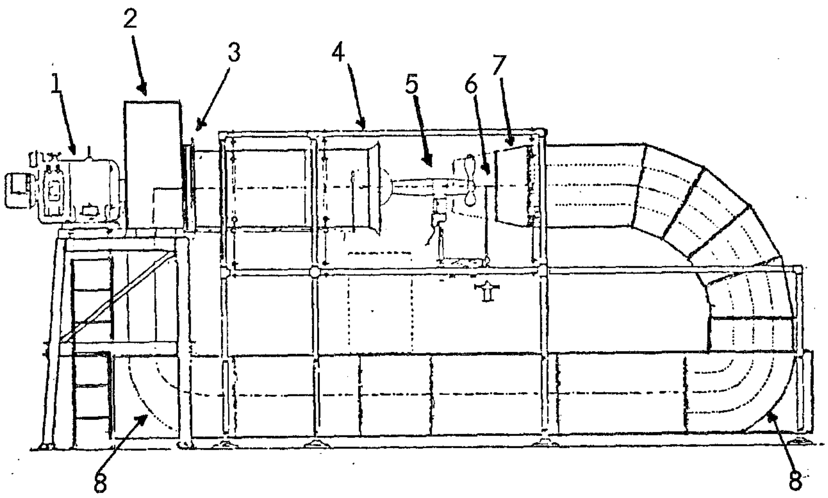


Figure 223 - Vertical plane air-duct wind-tunnel

The design presented in Figure 223 has the following major parts:

(1) d.c. variable-speed electric motor, Ward-Leonard speed control (example power rating: 20 kW);

(2) radial blower, statically and dynamically balanced (example air-stream capacity: 270 m^3 s^{-1}, speed up to 30 m s^{-1} through an outlet orifice cross-section of 42 cm diameter);

(3) iris-diaphragm additional speed control;

(4) guard rails of working platform (elevated);

(5) test-space (open) with an anemometer under test;

(6) Pitot-tube air-speed probe;

(7) changeable outlet cone (example air-speed change: maximum up to 40 m s^{-1}, if the tapered outlet is used);

(8) air-duct with honeycomb airstream turbulence filters in the bent portions.

The wind-tunnel discussed provides possibilities for a fine control of the airstream speed within limits of 1 - 40 m s^{-1}.

The basic principle of the Ward-Leonard motor-speed control (see Part 3) is based on the use of an a.c. motor/d.c. generator electric source of variable voltage and a d.c. electric blower motor having an independent (rectifier-fed, rheostat-controlled) field coil.

A different air speed can be obtained through the motor-speed control by the use of a d.c. fan-motor fed by a thryristor variable-pulse-frequency current source.

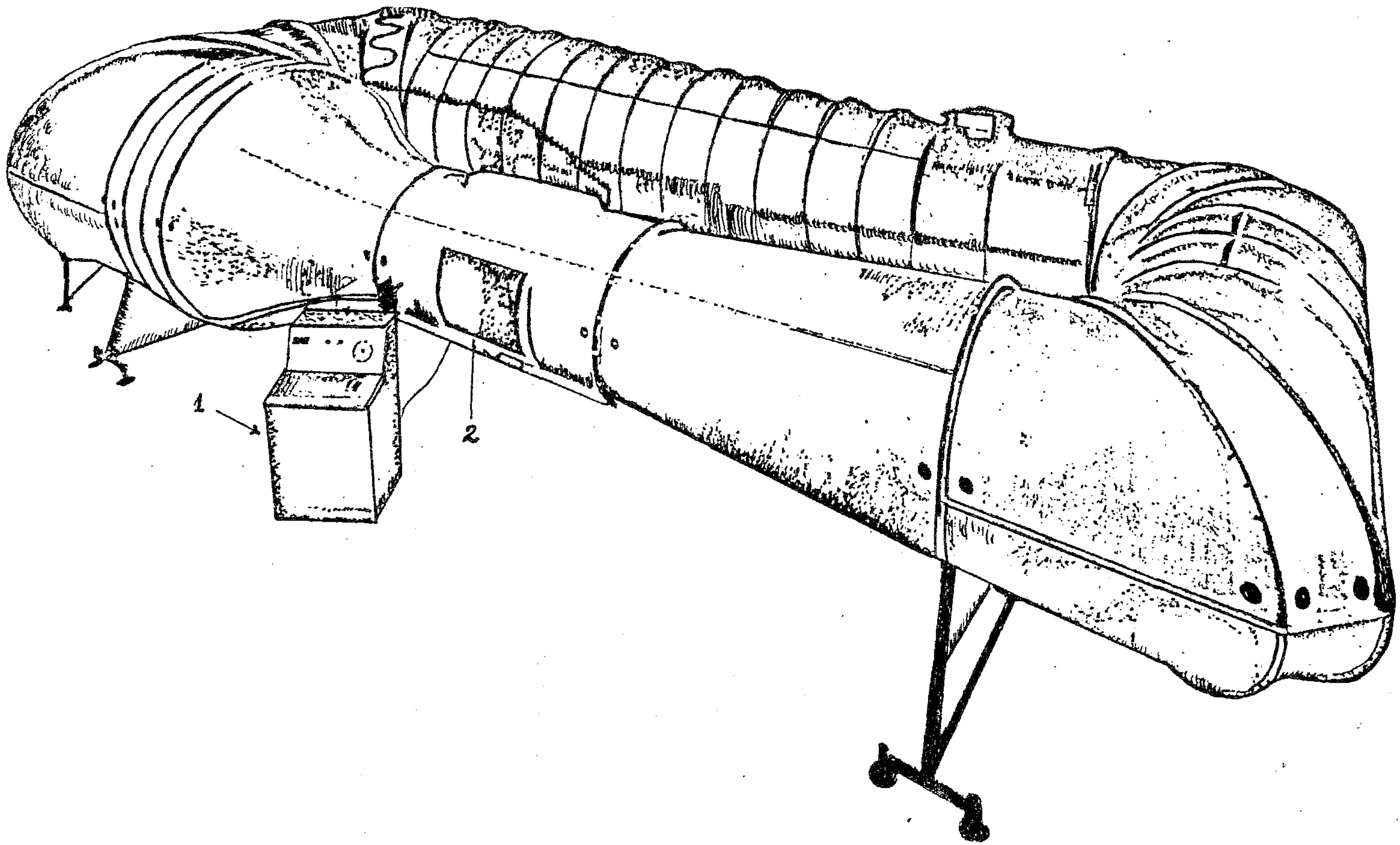


Figure 224 - Horizontal plane air-duct wind-tunnel: 1 - Air-speed control station;
2 - Test-space

Wind-tunnels used for test and calibration of meteorological equipment range in maximum attainable speed (up to 60 m s^{-1}) and test features.

The basic requirements for wind-tunnels concern the time and space constancy of the air speed inside the working space, absence of speed gradient within the test cross-section area of the tunnel and satisfactory speed-control facilities:

- Time and space variability of the air speed within the test space should be less then one per cent of the actual test speed;

- Repeatable air-speed control should be possible, starting from at least one metre per second up to the maximum speed of the equipment;

- The air-stream direction variations from the axis of the duct should be less than a few tenths of a degree.

The relationship between the load and the required power for different kinds of blower is shown in Figure 225.

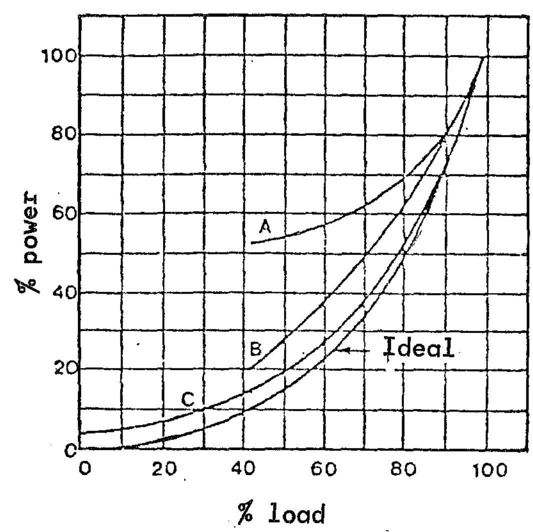


Figure 225 - Performance of various blowers: A - radial (centrifugal) blower; B - variable r.p.m. fan propeller; C - variable-pitch fan (varofoil)

The performance of the variable-pitch fan (variable angle of attack of the blades of the fan) comes closer to the ideal performance. The practical realization of the variable pitch fan, however, is rather complicated; this is why the variable revolution per minute fan is in more widespread use.

17.8.2 Standard instruments

The basic airstream — speed measuring instrument in use for calibration and testing purposes is the combined Pitot-tube and Krell micromanometer, already discussed in detail in Part I of this compendium. It should be kept in mind that the pressure differences measured at the various test air speeds are rather small:

- At v = 1 m s^{-1}, a pressure difference of about 0.06 mm water column;

- At $v = 20\ m\ s^{-1}$, pressure difference of about 25 mm water column.

An airstream - pressure difference of one millimetre water column is equal to one kilogram per square metre at a temperature of 4^oC.

The Krell micromanometer is a variable-sensitivity device: measurements can be taken at different angles of the manometric tube. The following formula is used:

$$p = 0.8\ a\ (l_2-l_1) = c(l_2-l_1)\ \text{(mm water column)} \qquad (1)$$

where:

0.8 is the specific weight of the alcohol used as a manometric liquid (at 15^oC);

0.8 a = c is the pressure constant of the manometer depending on the slope of the manometric tube according to the following table:

Pressure constant of the micromanometer for alcohol $c = 0.8\ \frac{g}{cm^3}$

Slope	1:100	1:80	1:50	1:25	1:10	1:5	1:2	1:1
c	0.008	0.01	0.016	0.032	0.08	0.16	0.40	0.8

The specific weight of the manometric liquid depends on the temperature.

Temperature coefficient of the specific weight of alcohol

Temperature ^oC	0^o	30^o	50^o
Multiply c by	1.014	0.986	0.967 (correction of equation (1))
Multiply k by	1.007	0.993	0.984 (correction of equation (2))

The airstream velocity is obtained from the equation:

$$v = \sqrt{(2g/s)\ 0.8\ a\ (l_2-l_1)} = k\sqrt{(l_2-l_1)}\ (m\ s^{-1}) \qquad (2)$$

where:

g = gravity acceleration ($m\ s^{-2}$);

s = specific weight of the atmospheric air ($kg\ m^{-3}$);

k = velocity coefficient ($2g\ 0.8\ a/s$);

l_2-l_1 = manometric difference (read-out).

Specific weight of air, s, (humidity 50%) for different values of P and t

Atmospheric pressure	720 mm	730 mm	740 mm	750 mm	760 mm	770 mm
Air temperature (°C)	s (kg m^{-3})					
0	1.221	1.239	1.255	1.273	1.290	1.307
10	1.177	1.193	1.209	1.226	1.242	1.259
20	1.134	1.149	1.165	1.181	1.197	1.213
30	1.092	1.108	1.123	1.138	1.154	1.169

Velocity coefficient, k, as a function of s and the slope of the tube

Slope of tube	1:100	1:80	1:50	1:25	1:10	1:5	1:2	1:1
s (kg m^{-3})								
1.09	0.380	0.424	0.537	0.759	1.200	1.697	2.682	3.795
1.13	0.373	0.416	0.527	0.764	1.179	1.667	2.634	3.727
1.17	0.366	0.409	0.518	0.733	1.158	1.638	2.688	3.663
1.20	0.362	0.404	0.512	0.723	1.144	1.618	2.556	3.617
1.23	0.357	0.399	0.505	0.715	1.130	1.598	2.525	3.573

Example: Manometric liquid, alcohol 0.8 g cm^{-3} at 15°C, tube graduation in mm

Read-out: l_1 = 1 mm; l_2 = 82 mm (averaged from five readings);

Difference: $l_2 - l_1$ = 81 mm;

Air temperature and pressure: t = 20°C, P = 730 mm;

s_{air}(kg m^{-3}): 1.15;

Slope of manometric tube: 1:10;

Velocity coefficient: k = 1.165 (interpolated);

Airstream velocity: $v = 1.165\sqrt{81} = 10.5$ m s^{-1}.

Microminiature rotational sensors (similar to the cup-wheel sensor) having optical converters, checked thoroughly against a standard instrument of a higher class, may be used in the capacity of working standards within the centrimetre-velocity range.

17.8.3 Calibration routines

Before the release of the wind tunnel for calibration procedures, its features must be studied thoroughly according to the requirements outlined in the discussion on calibration equipment.

With the help of the Pitot tube and micromanometer arrangement, the velocity profile must be measured at a minimum of two cross-sections along the axis of the duct within the limits of the working space and at ten spots along two mutually perpendicular diameters thereof. The magnitude of the velocity measured and obtained is an average of ten individual measurements per measuring spot.

The results of the measurements are presented in graphical form. They are examined for irregularities and the measurements are repeated three times in the course of one week and the results studied again for time variations.

One homogeneity of the airstream velocity inside the test-space of the wind-tunnel has been achieved, the calibration of meteorological instruments can commence.

(1) The first step in the calibration routine is an external examination of the instrument. It is assumed that all mechanical and electro-mechanical instruments entering the premises of the AL are thoroughly checked, cleaned and oiled beforehand in the relevant workshop.

The check-up is specific for each kind of instrument but, generally, the operational condition of the instrument is examined for each of its links (mechanical and electrical).

(2) When its satisfactory operational condition is established beyond doubt, the instrument is attached to the testing stand inside the test-space of the wind-tunnel and is subjected to a break-in test-run within its measuring range.

(3) The test-run finished, the lower (starting) threshold of the anemometer is measured. The wind-tunnel velocity is increased gradually, starting from 0 $m\ s^{-1}$. It is desirable to run each velocity increment of about 0.1 $m\ s^{-1}$ for at least five minutes, observing carefully the first indication of the calibrated instrument - the lower velocity threshold.

(4) Calibration of the instrument is carried out at least at ten test points of the calibration course: five along the ascending-velocity leg and five along the descending-velocity leg. At each test point, five readings of the standard instrument are taken, increased to ten if there are pulsating movements of the manometric liquid inside the manometric tube. The readings of the standard instrument are corrected accordingly and averaged. The recommended test-points are 1, 2, 4, 10 and 20 $m\ s^{-1}$.

(5) The averaged data from the comparison are entered on the calibration form and are plotted separately on a graph: tested instrument readings/ standard instrument readings, the scales of ordinate and abscissa equal.

(6) The calibration curve of the anemometer should be a straight line for instruments having a linear scale.

(7) Calibrated instruments are "accepted" or "rejected" depending on the necessary correction amount and scatter postulated for each kind of anemometer (see below).

The calibration normals for various field wind-measuring instruments are as follows:

(a) Heavy-plate anemometer (Wild type):

(i) Within the wind-velocity range 1 - 8 m s^{-1}, the error should be less than 0.5 m s^{-1};

(ii) Above 8 m s^{-1} wind velocity, tolerable error should be considered as less than 1 m s^{-1};

(iii) Wind-direction error in all sectors should remain less than 10^{o};

(b) Hand, mechanical anemometer:

(i) Lower velocity threshold less than 0.8 m s^{-1};

(ii) Deviation of test values should remain smaller than

- $\pm$ 0.05 m s^{-1} within the range 1 to 5 m s^{-1};
- $\pm$ 0.1 m s^{-1} within the range 5 to 20 m s^{-1};

(c) Hand, induction-type anemometer:

(i) Lower velocity threshold should be less than 1.5 m s^{-1};

(ii) Scale correction should remain within $\pm$ (0.5 + 0.05 v) m s^{-1};

(d) Electrical anemograph:

(i) Lower velocity threshold: less than 1 m s^{-1};

(ii) Deviation of test values from the averaged curve should remain smaller than: $\pm$ (0.5 + 0.02 v) m s^{-1};

(iii) Wind-vane accuracy should be better than $\pm$ 10^{o} at v = 2 m s^{-1}.

"Rejected" instruments are returned to the workshop for a second examination and eventual repair. (For updated anemometers' accuracy requirements, see Guide to Meteorological Instruments and Methods of Observation', WMO-No.8, 5th edition.)

17.9 Solar-radiation laboratory

Solar-radiation measurements are increasingly needed, on a global scale, for the purposes of science, industry and agriculture, More and more field stations are carrying out such measurements, a basic laboratory unit to handle the periodic maintenance and calibration of a few fundamental solar-radiation instruments is therefore necessary.

The components of the solar radiation measured at the Earth's surface are:

(a) Direct radiation for the solar disk;

(b) Diffuse radiation from the sky;

(c) Total radiation from the Sun and sky.

The instruments used in the measurement of these three components, subject to a meteorological control from the solar-radiation laboratory (SRL), are:

(a) Pyrheliometers, first and second class;

(b) Pyranometers, with or without shading attachment, first, second and third class.

The auxiliary instruments and equipment subject to a performance control from the SRL are the following:

(a) Moving-coil indicators (galvanometers, micromanometers, millivoltmeters);

(b) Mechanical and electrical (electronic) recorders;

(c) Mechanical and electrical (electronic) integrators of the solar-radiation components.

The meteorological control (test, comparison, calibration) of solar-radiation instruments may be made in either (or both) natural or laboratory conditions. The present discussion of the SRL objectives will be confined to routine activities carried out in conditions where the instruments are tested and calibrated, using solar-radiation energy as a source.

17.9.1 Standard instruments

The fundamental solar-radiation reference standard instrument is the Ångström compensation pyrheliometer (in some countries, the silver-disk pyrheliometer certified as such after comparison with a recognized standard instrument (e.g. a regional standard pyrheliometer).

The laboratory working-standard instrument may be a first class pyrheliometer (Michelson bimetallic, thermoelectric pyrheliometer), which should be compared to a higher-class standard instrument, the stability of its calibration characteristics being checked every five years.

For the purposes of meteorological control of pyranometers, working standard pyranometers, calibrated and certified as such, may also be used.

A discussion of the operation principles of all the above-mentioned radiation instruments is given in Part I of this compendium.

The accuracy classification of some radiation instruments subject to the present discussion are presented in the table below:

Accuracy classification of pyrheliometers and pyranometers

Parameter*:	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)
Pyrheliometer											
Reference standard	±0.2	±0.2	±0.2	±0.1	±0.5	25 s	-	-	0.1 unit	0.1	0.1 s
1st class	±0.4	±1.0	±1.0	±1.0	±1.0	25 s	-	-	0.1 unit	0.1	0.3 s
2nd class	±0.5	±2.0	±2.0	±2.0	±2.0	1 min	-	-	0.1 unit	±1.0	-
Pyranometers									Recorded errors		
1st class	±0.1	±1.0	±1.0	±1.0	±1.0	25 s	±3	±3	0.3		
2nd class	±0.5	±2.0	±2.0	±2.0	±2.0	1 min	±7	±7	±1.0		
3rd class	±1.0	±5	±5	±5	±3	4 min	±10	±10	±3		

*(a) = sensitivity (mW cm^{-2})
(b) = stability (%)
(c) = temperature (%)
(d) = selectivity (%)
(e) = linearity (%)
(f) = maximum time constant
(g) = cosine response (%)
(h) = azimuth response (%)
(i) = error in galvanometer
(j) = milliammeter error (%)
(k) = chronometer error

17.9.2 Meteorological and performance control over solar-radiation measuring instruments - routine activities

17.9.2.1 Testing of the moving-coil indicator

Moving-coil indicators: millivoltmeters, microammeters and galvanometers have the same operating principle (see Part 3). Moving-coil instruments are used as indicators of the solar-radiation component measured, thus the overall accuracy of the measurement depends greatly on their performance characteristics and general condition.

A general approach to the testing procedure of the moving-coil indicator as outlined below:

(a) Outer examination of the instrument;

(b) Preliminary performance test;

(c) Measurement of the internal resistance of the instrument;

(d) Check-up of the electrical insulation: body/electrical system;

(e) Mechanical balance of the indicating system, test;

(f) Scale-correction determination: current-meter and voltmeter test;

(a) The outer examination of the instrument is aimed at revealing instrument defects, likely to affect adversely its performance characteristics:

- Examination of the general physical condition of the instrument: body, body protective paint, scale, indicator-needle, electrical terminals, arresting mechanism (if available), zero-adjustment screw, thermometer (if available), carrying case;

(b) The preliminary performance test is aimed at revealing whether the indicating system is operational or damaged (burn-out, corrosion, interruption of circuit, mechanical failure, etc.).

Two simple devices can be used in the preliminary performance test of the moving-coil indicator: thermocouple thermoelectric power source, battery-driven voltage divider (Figure 226).

The thermocouple thermoelectric power source consists of two conductors - copper and constantan - each about 20 cm long and 0.3 to 0.5 mm diameter, soldered together at one end in such a way as to increase the mass of the soldered tip (a 3 - 5 mm diameter solder drop is left to solidify around the tip of the thermocouple). The free ends of the thermocouple are connected to the terminals of the tested instrument: the copper conductor is connected to the positive terminal and the constantan conductor to the negative terminal of the meter. The preliminary performance test with this device consists of heating up the soldered top of the thermocouple, first with the fingers then (if no deflection of the indicating needle is observed) a lighted match (taking care not to melt the solder). Depending on its sensitivity, the indicating needle of an instrument in an operational condition should deflect. When using the thermocouple tester it should be remembered that its output voltage is a few tens of microvolts per degree Celsius.

The voltage-divider tester is presented in Figure 226. Its power source is a dry battery of 1.5 V. A fractional voltage appears at the output terminals of the divider, depending on the position of the switch, S (the smallest testing voltage is obtained with S in position 1). In order to avoid damage to sensitive tested indicators, the divider is provided with a push-button switch, which is depressed after the test voltage has already been selected.

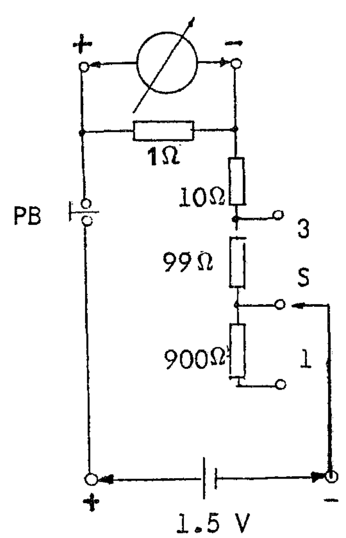


Figure 226 - Voltage divider

The tested instrument's terminals are connected to the output of the voltage divider with regard to polarity. The selector S is switched to position 1. If no deflection of the indicating needle of the instrument ensues, S is switched to position 2 and then to position 3. Non-deflection is an indication of the inoperational condition of the instrument and a necassary repair;

(c) A wheatstone bridge having a sensitive galvanometer as a zero-indicating instrument is used in the measurement of the internal resistance of the moving-coil indicator under test. A multiflex galvanometer 10^{-7} A-scale division, or better, is a suitable zero-indicator. A decade-variable resistor is used as a comparator R_d and the resistors connected in the legs of the bridge are temperature-stable wire-wound resisters.

The power source is a dry-battery of 1.5 V. used in a potentiometric configuration, permitting a choice of the bridge voltage starting with 0 V.

With a bridge voltage equal to zero (potentiometer P sliding contact at the extreme left) the tested instrument terminals are connected to points (1) and (2), observing polarity. The bridge voltage is slowly increased and the decade's resistance R_d adjusted in such a way as to obtain zero current in the diagonal of the bridge. The bridge voltage is increased enough that the tested instrument's deflection reaches the middle of the scale and the R_d value is again adjusted to obtain "zero" diagonal current.

The value R_d is read-out and, using the proportion $\frac{R_x}{R_1} = \frac{R_d}{R_2}$ the value of the internal resistance of the tested instrument R_x is found.

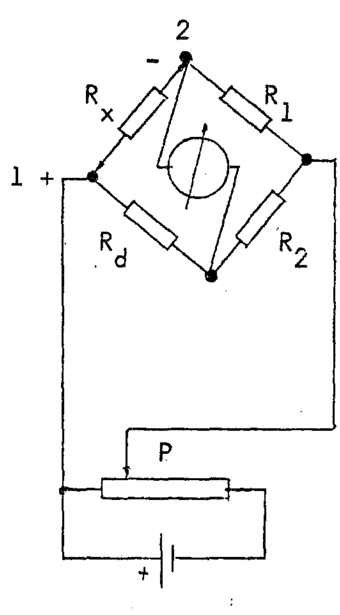


Figure 227 - Wheatstone bridge

The internal resistance of the tested instrument is necessary for optimizing the sensor/indicator circuit and the calculation of an additional resistance in case the voltage range of the tested instrument needs an increase;

(d) The check-up of the insulation resistance: body of the instrument/ electrical system of this same is done with the help of a megohmmeter. In no case should this resistance be lower than 50 MΩ at an ambient temperature of 20^{o}C;

(e) A simple test is used to find out whether the mechanical balance of the indicating system of the instrument is satisfactory: placing the instrument on a sloped plane meeting the horizontal plane at an angle of 5^{o} should not cause a deflection of the needle greater than:

- 3 scale divisions for a galvanometer;
- 0.5 scale division for a millivoltmeter or microammeter;

(f) The scale correction of the tested instrument is obtained by the use of either the circuit diagram in Figure 228 (voltage scale-correction tester), or that in Figure 229 (current scale-correction tester):

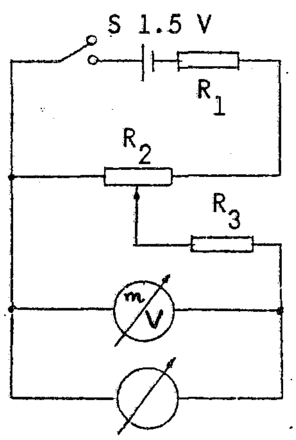


Figure 228 - Voltage scale-correction tester

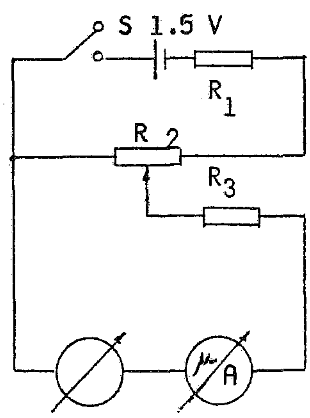


Figure 229 - Current scale-correction tester

Millivoltmeters and microammeters of an accuracy class 0.2 to 0.5 and a scale of 100 divisions (certified instruments) are used as standard instruments in the determination of the scale corrections. The power source, usually a dry battery of 1.5 V , should have a large enough ampere-hour rating to maintain a voltage constancy during the measurement better than 0.1 per cent. The control potentiometers should be wire-wound precision pots, ensuring high temperature stability.

Firstly (with power source switched off), the zero adjustment is made of the tested instrument. Secondly, a comparison of the readings along an ascending leg of voltage values is made at every fifth scale division between the 0 and the full-scale deflection of the tested instrument. The comparison is repeated along the descending leg of the voltage scale. Thirdly, a second check of the zero of the tested instrument is made.

The scatter of the read-outs of the tested instrument should not go beyond 0.3 scale division.

The same testing procedure is carried out with the current-measuring instruments, using the circuit in Figure 229.

17.9.2.2 Testing of recording instruments

Mainly, two types of recording instruments are used in connexion with the solar-radiation sensors of the electrical type:

(a) Spot-recorders (millivoltmeters, microammeters);

(b) Electronic potentiometers.

The procedures outlined in the previous paragraph are valid for the spot-recording millivoltmeters and microammeters.

The testing of electronic potentiometers is beyond the scope of this discussion and is beyond the scope of activities of a solar-radiation laboratory having the limited objectives already outlined.

17.9.2.3 Testing and comparison of electrical direct solar-radiation measuring instruments

Prior to testing and calibration, the direct solar-radiation measuring instruments are subjected to the following procedures:

(a) General examination of the instrument, aimed at judging its operational condition;

(b) Measurement of the resistance of the thermopile, an entity to be used later in the evaluation of the instrument's sensisitivity;

(c) Measurement of the electrical insulation resistance between the thermopile and the body of the instrument;

(d) Determination of the tested instrument's scale-conversion coefficient and sensitivity;

(e) Determination of the time-dependent characteristic of the instrument (its lag).

The adequate operational condition of the tested instrument is examined through the examination of its various parts: body and body protective cover (chromium plating or paint), condition of pedestal, joints, scale and solar-disk aiming device, adjusting screws, filters, accessories. An instrument found to be in complete operational condition is subject to the further procedures outlined above.

The resistance of the thermopile can be measured using the Wheatstone bridge already described. In order to eliminate possible errors stemming from thermoelectric potentials, the measurement is carried out twice, alternating the output terminals of the tested instrument with respect to the polarity-marked terminals of the bridge.

The electrical resistance of the instrument body/thermopile is tested using a megohmmeter. A minimum of 1 MΩ resistance should be found between the body and the thermopile terminals, the measurement being carried out at a temperature of 20°C.

The scale-conversion constant of the instrument (697.8 10^{-2} W m^{-2} mV^{-1}) is found through comparison with a standard instrument (primary or secondary one). Both instruments are trained at the Sun and the readings taken. The value of the solar radiation, as obtained from the standard instrument, should be corrected accordingly, using the certificate of the standard instrument (possibly a Michelson working standard). Care should be taken that the comparison is carried out in conditions of clear circumsolar sky, in the case of two instruments having different opertures.

The sensitivity of the instrument is found through the comparison with the standard instrument using the following relationship:

The expression for the electromotive force of the sensor (e.m.f.), E is:

$$E = I(R_1 + R_2) \tag{1}$$

where:

I = $\alpha.n$ = the current in the circuit thermopile/indicator;

α = scale division of the indicator;

n = number of scale divisions indicated;

R_1 = internal resistance of the instrument (thermopile);

R_2 = external circuit resistance.

Bearing in mind that the internal resistance $R_1 = R_{th}$ already established through measurement (see section 17.9.2.1 (b)) and $R_2 = R_g + R_d$, where R_g is the moving-coil indicator resistance and R_d is an additional resistance in the circuit, through the application of Ohm's law, the following expression is obtained:

$$K.S = \alpha.n(R_{th} + R_g + R_d) \tag{2}$$

where:

S = the true value of the solar radiation, as obtained from the standard instrument;

K = the tested instrument's sensitivity.

Finally:

$$K = \frac{\alpha.n(R_{th} + R_g + R_d)}{S} \tag{3}$$

With the comparison procedures, a minimum of 10 readings is taken at each test point if the solar radiation is sufficiently stable (according to a recording instrument). The number of readings is increased to 20 in conditions of a varying radiation.

For the time-dependent characteristic of the instrument is taken the time necessary for its radiation indication to drop down to a 0.5 per cent difference from the actual zero, after its sensor has been completely shaded from the Sun. The measurement is carried out in a straightforward fashion, as follows:

- The instrument is trained at the Sun and after about a minute a reading is taken. The reading is corrected, if necessary, and 0.5 per cent of the reading is calculated, expressed in scale divisions;

- The sensor is shaded, simultaneously switching on a stop watch. When the indicator needle reaches the calculated 0.5 per cent, the stop watch is stopped. The time measured is the desired lag characteristic of the tested instrument.

The time-dependent characteristics of tested and standard instruments are taken into account in the comparison procedures.

The standard instruments employed in the comparison may be either high-class compensation, possibly silver-disk pyrheliometers, carefully standardized Michelson bimetallic or thermoelectric Linke-Fuessner instruments.

A sufficient number of comparison readings should be made in order to ensure that a representative value for the constant of the tested instrument is obtained over as wide a range as possible of temperature and solar intensity.

The ranges of ambient temperature and solar intensities are stated in the comparison certificate of the tested instrument. For the comparison of reference standard instruments, the sky condition, with reference to turbidity measurement, is shown in the certificate as well.

Pyrheliometers screened by quartz windows are compared with instruments which have no windows interposed in the solar beam.

Primary sub-standard pyrheliometers are subjected to a comparison with the primary standards in a regional radiation laboratory.

17.9.2.4 Ångström pyrheliometer auxiliary electrical equipment

The following auxiliary electrical equipment will be necessary for the Angström pyrheliometer, which is usually employed in the capacity of a standard instrument:

(a) Multi-range (0 - 250 and 0 - 500 mA) class 0.25 (or better) d.c. milliammeter, certified as regards scale and temperature corrections;

(b) Reflecting or needle galvanometer of a sensitivity 10^{-7} A per scale division (or better); internal resistance 50Ω (or better) and period not longer than seven seconds;

(c) Two rheostats of $50\,\Omega$ and $5\,\Omega$, respectively, safe current one ampere, rheostat slides at least 30 cm long;

(d) Interconnecting leads.

17.9.2.5 Testing and comparison of the Michelson bimetallic pyrheliometer

The sensor of the Michelson pyrheliometer is a blackened bimetallic strip, which bends under the heat of the solar radiation. The deformation of the strip is observed through a microscope against a scale (see Part I of this compendium). The readings of the instrument are strongly dependent on the ambient temperature. A temperature-correction screw, in the Michelson-Marten model directly graduated in degrees Celsius, makes possible the elimination of the temperature effect of the ambient air.

The comparison routines concerning the Michelson instrument are started, as usual, with a general examination of the pyrheliometer.

The tested and standard instruments are installed at the comparison site and are levelled. A period of time is allowed for both of them to attain the temperature of the surrounding air. Using the temperature-correction screw of the Michelson pyrheliometer, the indicating mark is brought to about one twentieth of a scale division in order to allow the indicating mark to remain within the view of the observer once the temperature of the instrument has fully adapted (i.e. about 30 minutes). (Both instruments are trained at the Sun.)

The calibration factor of the tested instrument is established through multiple comparison readings of tested and standard instruments at various temperatures and solar intensities and is expressed as a calorific value of one scale unit.

The scatter of the individual values of the calibration factor should remain smaller than five per cent of the value of the averaged calibration factor.

17.9.2.6 Testing and comparison of total and diffuse solar-radiation measuring instruments

There are four principal methods of calibrating pyranometers:

(a) Comparison of the tested instrument with a sub-standard pyrheliometer using the Sun as a source;

(b) Comparison with a standardized pyranometer of the same, or a different type, in natural conditions;

(c) Comparison of the tested instrument with a standardized pyranometer in laboratory conditions using an artifical source (lamp) and an optical bench;

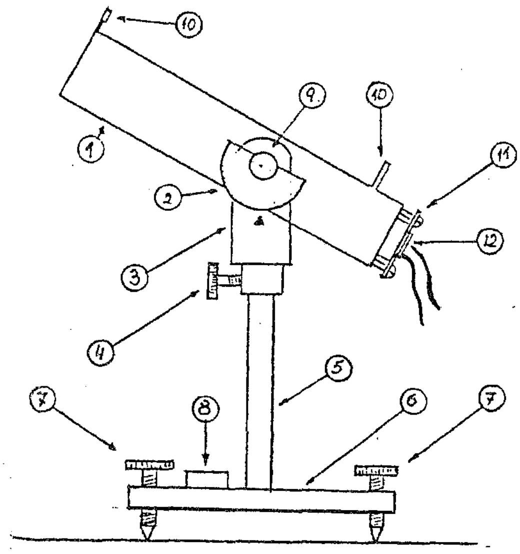
(d) Comparison of the tested pyranometer with a standardized one in laboratory conditions using an integrating sphere.

As with the foregoing, our discussion will be concerned only with calibration procedures in natural conditions.

Thermoelectric pyranometers (Moll-Gorczynski, Eppley, Yanishevskii) may be compared with a subsidiary standard pyrheliometer for normal incidence of the solar radiation, using the tubular mount pictured in Figure 230. The tubular mount with the tested instrument's sensor mounted at its rear end enables the instrument to be trained at the Sun, while cutting off the diffuse component of the sky radiation. The scale-conversion coefficient obtained is known as "normal incidence scale - conversion coefficient".

The tubular device is a metal pipe of suitable diameter and length, provided with a tight-fitting clamp for the attachment of the sensor at its rear end and diaphragms near its front orifice limiting the solar angle at which the sensor is irradiated by direct solar dadiation to about 10°. The pipe is painted black on the inside.

A sighting device and an elevation-angle setting device enable the exposure of the sensor of the tested instrument normally to the sun-beam.



(1) diaphragmed pipe
(2) elevation-angle dial
(3) supporting fork
(4) azimuth arresting screw
(5) supporting column
(6) pedestal
(7) levelling screws
(8) spirit level
(9) elevation-angle arresting screw
(10) sighting device
(11) sensor clamp
(12) calibrated sensor

Figure 230 - Tubular device used in normal incidence comparisons of radiation

The comparison procedures are started, as already pointed out, under the testing procedures of pyrheliometers, with a general examination of the tested instrument. Special attention should be given in the examination to the condition and transparency of the glass dome of the sensor, as well as the condition of the optical black and white lacquers used in the painting of the sensor's "hot" and "cold" thermopile junctions.

Further, the resistance of the thermopile is measured following the procedures and using the measuring bridge (Figure 227) already described. The electrical insulation resistance body/thermopile is checked, as well as the time-dependent behaviour of the instrument, following the procedures outlined in connexion with testing pyrheliometers.

The comparison of the pyranometer and the standard pyrheliometer with normal incidence of the solar radiation is a straightforward matter. The readings of the two instruments trained at the Sun should be made with due account being taken of the lag-characteristics of the two instruments and should cover as wide a range as possible of ambient air temperature and solar elevations.

The normal-incidence scale-conversion coefficient is obtained by averaging a sufficiently large number of comparison readings, using equation (3) from section 17.9.2.3.

The sensitivity of the tested instrument will generally depend on the azimuth and elevation angle of the radiation source. A correction coefficient can be obtained for the correction of these two errors under laboratory conditions. The azimuth angle correction may actually be dropped because the azimuth error is introduced through the non-homogeneity of the glass dome of the sensor and, by always installing it in the same manner, the effect of this error is greatly diminished.

As far as the elevation-angle correction is concerned, with which the normal-incidence scale-conversion coefficient should be multiplied when the instrument is used in routine measurements with its receiving surface horizontal, a correction coefficient F_h can be obtained by exposing the tested instrument (carefully levelled) to a parallel beam of artificial light, whose incidence angle can be controlled within the limits of 10^o to 90^o. The value of F_a can be within the range 0.9 to 1.1 for low elevation angles (10^o to 60^o), remaining almost 1.0 above 60^o elevation of the solar disk.

The results of the elevation-angle correction testing is presented in a graphical form as a plot of the values of F_h against the solar-disk elevation angles.

The comparison results concerning the tested pyranometer are entered in the calibration certificate of the instrument, together with an indication of the temperature range of the test procedures, general meteorological conditions during the test period, solar-elevation angle ranges and solar-elevation correction-coefficient graph.

17.9.2.7 Testing of the bimetallic Robitsch-type actinograph

The Robitsch-type actinograph is a total solar-radiation recording instrument of lower accuracy - not better then five per cent. Instantaneous values obtained from measurements with the instrument are reliable only when radiation values are changing very slowly.

The sensitivity of the actinograph depends on many factors, such as ambient temperature, radiation intensity, elevation and azimuth of the Sun. The sensitivity is liable to slow change because of deterioration of the sensor's optical point cover, the sensor itself being not totally protected from the weather.

The comparison of the actinograph is best done with an electrical pyranometer in natural conditions over a wide range of temperature, solar-disk elevation and general meteorological conditions.

The general examination of the instrument prior to testing procedures is focused on:

(a) Condition of the glass dome, bimetallic sensing strips, paint of the sensor;

(b) Condition of the mechanical magnification system and recording mechanism;

(c) Condition of the clockwork.

The first test of the actinograph is aimed at establishing the ambient temperature-compensating action of the sensor. A test run of the instrument with its glass dome protected from radiation and the case subjected to a temperature step-change of 20^o should not cause changes of the baseline greater than one-half of the smallest scale division.

The actual comparison of the actinograph with the standardized electrical pyranometer is carried out at a proper outdoor site, the two instruments being placed side by side and the installation prescriptions observed (See Part 1 of this compendium). The comparison readings are taken every 15 minutes, preferably avoiding periods of marked changes in the radiation as a result of other meteorological factors. The test period should be long enough to cover a wider temperature and solar-elevation range.

The simplest procedure of processing comparison results is the graphical one, whereby the values of the observed radiation according to the standardized instrument are plotted against the corresponding values read-out from the tested instrument. The plot should be a straight line, the slope of which renders the calibration conversion coefficient. The procedure is presented in some detail in Part 1, Chapter 9.

17.10 Failure statistics of meteorological instruments

Meteorological instruments fail at random and occurring at any time with little or no warning. Generally, instrument failure may be caused by the effect on them of the environment, human error or wear-out of certain components with time.

Meteorological instrument failures may be divided into two major groups:

(a) Instrument break-down and a complete cessation of their functioning;

(b) Deterioration of the instrument's performance characteristics, (abrupt or gradual) and a resulting malfunction.

Whatever the kind of instrument failure, the end result from a meteorological point of view will be either loss of information or erroneous information. Both cases are equally unacceptable as they may lead to useless, even misleading, secondary meteorological information, which may have a serious, adverse economic impact.

Measures which may be taken to fend off such undesirable effects are the periodic monitoring of instruments' performance characteristics, the use of stand-by instruments and immediate replacement of defective or broken-down ones. Failed instruments are subjected to maintenance and repair, as well as calibration.

Control of the meteorological measuring-instrument characteristics, repair and calibration falls in the area of responsibility of the maintenance workshops and calibration laboratories.

The stochastic problem of instrument failure may be approached statistically. An accurate and complete log must be kept of all instrument failures recording all the information about each failure and failed instrument, which may later lead to conclusions applicable to planning the activities of the workshops and laboratories as well as planning replacement instruments, components and spare parts thereof.

In order to ensure the continuous acquisition of valid primary meteorological information and the high efficiency of the workshops and laboratories dealing with meteorological instruments, careful planning of the maintenance, repair and calibration activities must be effected.

The Meteorological Service departments handling the instruments used in the observing network should be familiar with the instruments' features, performance merits and deficiencies, general conditions on their installation site, the capabilities and working habits of the personnel handling them. This knowledge is usually accumulated in an informal manner by the technical staff in the form of professional experience but a short-cut is possible through an organized, statistical approach. An important advantage of the statistical approach is the quantitative character of the conclusions obtained as opposed to the qualitative value of the experience of technical personnel with long years of service and the "traditional" approach to the problem.

The statistical approach to the instrument-failure problem entails more work involved in completing statistical forms for each individual failure case, and for each individual instrument passing through the workshops or the laboratories on its way to the field station. It should be noted that this is the total population of meteorological instruments used in the field, since the despatch of old as well as new instruments to the various field stations should be recorded by the department handling the instruments' statistics.

The statistical approach is aimed at revealing important facts connected with the use, maintenance, repair and calibration of meteorological instruments. To list the more important ones:

(a) Performance features, reliability, durability, stability of calibration characteristics under operational conditions;

(b) Storage features (mainly in terms of calibration) of various models and makes of instrument;

(c) Typical failures, frequency of the various kinds of failure for the different models and makes of meteorological instrument;

(d) Frequency and kind of environmental causes of instrument failure and their connexion with specific field stations;

(e) Frequency and kind of human error as causes for failure and their connexion with observing personnel (inadequate qualifications, negligence, etc.);

(f) Use of consumables and spares;

(g) Temporal distribution of maintenance, repair and calibration activities.

An instrument statistical form is suggested (shown below) which is prepared in duplicate, with one copy accompanying the instrument, while the other is kept in the department's file.

As is evident from the statistical form suggested, part of the information concerning the life history of the filed instrument is filled in by the duty-station personnel and part of it by the workshop and laboratory staff. The filing clerk should ensure that the two copies of the form - the one accompanying the instrument and the one on file - are both kept up to date. The filing clerk should also be responsible for the extraction of data from the statistical forms in a way that will facilitate planning the supply of materials and spares, as well as the workload of the maintenance organization. The wider the scope of meteorological instruments in use and the higher their technological level, the more useful will be the failure statistics for planning supply, maintenance and repair.

As automation of meteorological data acquisition increases, so the traditional methods of planning, based on long-term experience and professional intuition, become less effective. The quality and speed of modern, automated data acquisition must be matched by the quality and speed of the organization which maintains the instrument.

INSTRUMENT STATISTICAL FORM

Issued, date ....

Kind of instrument on file: ....

File No.: .... Store location: ....

Make, model, year of release: ....

Date of despatch to the station: .... Station: ....

Name/grade of station personnel responsible for the instrument:

(1) .... (2) ....

(3) .... (4) ....

Major adverse environmental characteristics of the duty station (frost, strong winds, corrosive pollution, etc.): ....

....

Instrument failure: nature/date/remedial action taken/observer on shift:

(1) ....

(2) ....

(3) ....

(4) ....

Instrument's periodic performance test date: results/staff member:

....

....

....

Re-calibration corrections date: scale range/correction/staff member:

....

....

....

Date of despatch: .... Date of receipt: ....

Transit time: .... Maintenance/repair/calibration time: .....

....

Number and kind of spares used: ....

Maintenance personnel: ....

Calibration graph attached: YES/NO

REMARKS: ....

....

....

Number of statistical form sheets preceeding the last one dated: ....

Filing clerk: ....